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INSTITUUT VOOR TOEGEPAST BIOLOGISCH ONDERZOEK IN DE NATUUR

ON THE MICROCLIMATIC PROPERTIES OF SHELTERED AREAS

THE OAK-COPPICE SHELTERED AREA

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On the microclimatic properties of sheltered areas

The oak-coppice sheltered area

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Chapter I

INTRODUCTION

The present publication contains the results of investigations into the characteristic microclimatic properties of an oak-coppice sheltered area.

Oak-coppice shelterbelts are long narrow strips of land, planted with oak-bark coppice. Sometimes the soil under the trees will be heightened by some decimetres.

These belts are frequently found in the sandy parts of the cultivated regions of the Netherlands, in places where the ground water level is not too high. Here they lie scattered among the fields, accentuating the edges of the plots and forming a rather picturesque scenery. Originally they were important as fences, and moreover for the wood supply and the production of tanning-materials. The last few decennia, however, these advantages have fallen into the background, whereas the disadvantages as the shading of the immediate surroundings and the root-competition have continued. Moreover, the farmers complained of the increased danger of night-frost in the sheltered areas, the scanty ventilation, owing to which in summer the grain after being reaped cannot dry fast enough, of the heat during the harvest proceedings in hot summer-weather, and of the trouble met with in those cases when mechanisation of agricultural activities is carried out. Hence some ten or twenty years ago many tillers cleared away their shelterbelts and at present many regions would be devoid of trees and bushes, if not afterwards the government had set bounds to the cutting down of those components of the countryside scenery. Other people argued that the problem of shelterbelts had been considered one-sidedly by the tillers, and inter alia they pointed out the favourable effect produced by these belts during periods of drought and strong wind, generally occurring in spring, during which part of the upper layers of the soil together with its most valuable components will be blown away rather frequently, and damage will be done to the crops (Van der Linde 1948*a*). A survey of such practical experiences in Holland was given by Van der Loeff (1948).

Also on biological grounds certain favourable influences were thought possible.

Thus the need of an exact basis for the judgment of the value of this and other kinds of woodplantings in the landscape made itself felt (VAN DISSEL 1942). The Institute for Biological Field Research T.N.O. (Instituut voor toegepast biologisch onderzoek in de natuur = I.T.B.O.N.) was instructed to perform the necessary investigations.

The Board of this Institute decided that, to begin with, the microclimatic aspect of the problem was to be investigated. Contact was made with the subdepartment for agricultural meteorology of the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut = K.N.M.I.), as a result of which the investigations could be made in co-operation with this Institute.

So the object of the I.T.B.O.N. was to lay a real basis for the judgment of the influence in the full sense of the word of all wood stands without characteristics typical of a forest on the surrounding crops, and of the culture-technical value of these landscape-components resulting from this influence.

In the framework of this plan the investigations now published try to give a description of, and to get a causal insight into the microclimatic properties characteristic of oak-coppice sheltered areas.

CHAPTER II

SURVEY OF LITERATURE

1. GENERAL

Naturally in the literature concerning our subject information on the influence of shelterbelts is often closely related with considerations of an agricultural character. In this survey we shall restrict ourselves as much as possible to the merely microclimatic aspect of the problem, while only where this may appear desirable its agricultural aspect will be touched upon.

NÄGELI (1941) gave a summary of literature, which seems rather complete, except for some important Danish publications (see below). Successively he deals with the influence of shelterbelts on the yield of crops, wind velocity above the contiguous fields, shiftings of the soil, snow-fall, evaporation, humidity and temperature of the air and humidity and temperature of the soil. The motive for compiling his summary was the want to increase agricultural produce which had made itself felt in Switzerland since long. Planting shelterbelts was thought to be one of the most adequate measures to arrive at this end. Some of the articles referred to by NÄGELI will also be dealt with in this summary. As for the others, we may as well refer to his survey. FRANSEN (1942) made an adaptation of it for Dutch readers, for whom the original work, written in German, is not accessible without difficulty.

Apparently NÄGELI did not know the publications by FLENSBORG, NØKKENTVED and their co-operators (1938 and 1940) on the influence of various types of stands on the windfield, while the circumstantial work of BATES (1911) is not spoken of to full advantage. The latter has approached many sides of the problem experimentally, and he deals with all but the same subjects as NÄGELI (1941). Partly BATES' conclusions and interpretations in the field of microclimatology are still valuable, partly, however, they have now lost their importance owing to newer insights. Moreover, he pays attention to the economic aspects of planting shelterbelts as such, and doing so he gives practical advice. The motive for BATES' investigations was the increasing soil erosion and the declinatory attitude regarding shelterbelts adopted by the farmers in the Middle Western States.

Of general importance is also a short publication of KREUTZ's (1938), in which likewise light is thrown on the problem from various sides, and in which it is approached on the basis of experiments made on small objects.

Of course we have gratefully taken advantage of GEIGER's book (1942). It is true it provides only little information on this special subject, but yet it has been of great value in forming an opinion of all sorts of details. As in this connection only the elementary principles of microclimatology were concerned, it seemed superfluous to refer to the book in all cases in which in our argumentation it had to be consulted. Only a few times we have thought it advisable to do so.

Finally two popular summaries of the shelterbelt-problem as a whole, compiled by VAN DER LINDE (1949 *a* and *b*), should be mentioned.

In the next pages the influences of shelterbelts on wind, precipitation, temperature, relative air humidity and evaporation as far as they are known from literature will be discussed in special sections. Incoming and outgoing radiation will be discussed along with temperature, as well as shading and reflection of solar radiation on the stands. Of course by incoming radiation we also understand light, which ought to have separate treatment, as it is a very important factor in the environment of the living plant. As, however, very little is known of the distribution of light as such in sheltered areas, we have not given a separate chapter to this subject.

It is to be expected that woodstands will also exercise influence over the distribution of the amount of carbondioxide in the air layers nearest to the ground. In the literature little attention is paid to this subject but "Untersuchungen hierüber sind im Gang" (WOELFLE 1943).

2. WIND

The wind-breaking influence of woodstands has often been the object of investigations. The observations made in this respect have usually been restricted to the horizontal component of the wind movement. The little information on the vertical component is nearly always of a hypothetic character.

GEIGER (1931) mentioned wind measurements made at Charkov, which had been continued since 1887 for 30 years. Half-way this period a spruce belt was planted. Now a reduction of wind velocity of 30 per cent was effected, which percentage rose to 47 per cent during heavy gales.

According to BUCHHOLZ (1941) the wind-reducing effect of windscreens used in many parts of Russia amounted to from 55 to 80 per cent. Also BODROFF (1936) mentions measurements performed in the Russian steppes. According to him 17-m high shelterbelts reduce the wind velocity on the average of 20 per cent, across a distance of 1 km when the velocity in the open varies from 2,5 to 3,0 m/sec. The reduction amounts to 30 per cent in velocities of 5 to 6 m/sec. So we are in this case concerned with a distance of nearly 58 times the height of the screen. As appears from these numbers increasing wind causes the relative shelter to be increased, which is in accordance with the result recorded by GEIGER (1931).

It will be clear that statements as the above are of little value if further particulars on the woodstand and place of observation are wanting. Without these data they do little more than confirm general experiences from daily life. For this reason the circumstances under which the observations were made should be fully stated. In the first place the distance of the place of observation from the stand should be taken into account. Moreover the latter should be described as exactly as possible. However, here we meet with the difficulty that the stand cannot be fully characterized by some simple features as measure, number of plants per unit of surface and botanical composition, because of the fact that the individual characteristics of the stand which are the results of its situation (BATES 1911), age and cultural circumstances, factors that cannot be described in a simple formulation, also influence its aerodynamic properties.

A rather great number of investigators have occupied themselves with the problem of the distance over which the influence of belts extends to leeward. DENUYL (1936) has summed up the results of older investigations into this subject. In this summary, in which BATES' results (1911) have been recorded as well, the divergent opinions clearly find expression. It is true the various authors agreed that as the distance to the stand increases its influence gradually decreases, and that the depth (width) of the sheltered zone is proportional to the height of the stand, but they disagreed regarding the distance (expressed in the height of the stand) across which this influence is of practical importance. This was in the first place caused by the different purposes the shelter had to answer, and also by the uncomparable objects and methods adopted in the investigations. The results recorded in Russian literature were not always obtained by means of wind measurements, but partly by means of estimates of the crops. DENUYL justly remarks that this cannot be called a reliable method. As a whole these investigations show that there is an appreciable protection in an area with a width of 20 to 25 times the height of the belt, provided that the wind direction is perpendicular or almost perpendicular to the stand. There is also a narrow area where protection is perceptible to windward of the stand.

In his own investigations DENUYL (1936) classified the wind-screens in a "scale of density". The first class comprises completely impervious screens — "barriers, such as hills, ridges, solid board-fences and paper". In the fifth class the screens of most open design are to be found. Moreover he arranged his data according to the wind velocity in the open. From the things observed he concluded first that the distance over which the sheltering influence extends would be directly proportionate to the density of the stand, and moreover, that the sheltering influence of a barrier is reduced when the wind velocity increases. The second conclusion was contrary to the views of BODROFF (1936) and GEIGER (1931), while the former is incorrect or at least very incomplete, as will appear from the results of modern investigations. Moreover it is to be regretted DENUYL did not say anything about the windfield of barriers of density class 1. In the eyes of modern investigators this class is made up most heterogeneously.

It is necessary to enter at once into DENUYL's second conclusion as here a subject of fundamental importance to the method of recent wind measurements in territories with hedges is broached (FLENSBORG, NØKKENTVED and their co-operators, 1938 and 1940, NÄGELI, 1943 and 1946, TANNER and NÄGELI, 1947). In these recent measurements the wind velocity in the sheltered area is always expressed in percentages of the wind in the open. In practice it is hardly ever possible to execute the measurements at all points at the same time. If now DENUYL's second conclusion were right a reliable picture of the distribution of wind velocity in the sheltered area could only be obtained in perfectly equable wind.

WOELFLE and NÄGELI (NÄGELI 1943 and 1946) have endeavoured to solve this problem. They proved that the percentage of protection at a fixed place in the sheltered area is all but constant in moderate wind velocities (about 2 to 7 m/sec.) and when screens are used of fairly moderate density. In the case of screens of a more open design no differences were observed in wind velocities from 1 to 9 m/sec. in the open. However, when denser screens were used the relative protection appeared to be somewhat smaller in moderate than in strong wind. NÄGELI (1946) supposed that for every wind-screen there must be a value of the velocity of the free wind above which the relative protection in sheltered areas is increased. The results obtained by GEIGER (1931) and BODROFF (1936) mentioned above are in accordance with this hypothesis. NÄGELI, however, fully realised that his conclusion was contrary to DENUYL's (1936). That's why he points out that during the passage of the wind through the screen two phenomena occur: reduction of the velocity of the air movement through the screen and a stronger air-current above the screen. He supposes the first to be responsible for the regularity found by him and WOELFLE, while under certain conditions the second should be able to cause the reverse situation by bringing about whirls. WOELFLE (1939, GEIGER 1942) also showed that in certain cases the typical qualities of the stand may also be of importance. In a barrier of spruce namely, he observed a distinct reduction of the relative perviousness. He explains this by assuming that the spruce branches act as the slats of Venetian blinds, which will be drawn nearer to each other in increasing wind.

It may be clear that, as yet, there is no uniformity of view into these problems. The main point, however, is that apparently in moderate wind velocities of 2 to 7 m/sec. the method used in modern wind measurements may be adopted without the risk of serious mistakes.

We might obtain a better insight into the matter, if we could lay down the properties of a stand in an exact formulation. As we have observed above this is, however, impossible.

The resistance the wind meets with is in a large measure dependent on the species of wood and the condition of the screen. When the shrubs are leafless the air between the branches will comparatively meet with the least resistance, because the round cross-section of the latter comes nearest to the streamline, so that formation of little whirls behind the individual branches will occur only to a small degree. If the branches are leafed, however, much of the effect of this streamline-form will get lost, stronger whirls will occur, and consequently the relative resistance to the movement of the air will increase.

Further, a hedge or a row of trees is not a stiff object, and as the wind increases the form of the shrubs or the trees will be changed.

A hedge of spruce, as we have already seen, will get denser. Moreover, when the wind velocity is small, the resistance, speaking physically, is directly proportionate to the velocity, whereas it is directly proportionate to the square of the velocity in the case of higher velocities. Of course this does not simplify the matter, while moreover, we are not always concerned with laminar currents but often with more or less turbulent ones, according to weather conditions and the hour of the day.

It may be expected that also the shape of the side view i.e. the cross-section at right angles to the longitudinal axis will influence the windfield. With reference to plans in the U.S.A. to construct an extensive network of windbarriers in the Plains, BATES (1934) writes:

"The next most obvious requirement to attain the above-described ends [the lee and the favourable influence on the crops resulting from it] is to so "construct" shelterbelts that they do not rise from the plain like the proverbial "sore thumb", but rather in the shape of a roof with a wide sweep at the eaves. This refers, of course, to the cross-section at any point at right angles to the long axis [1]). The plan is in sharp contrast to most of the old, extensive belts and groves, which are unprotected on the sides, free from limbs below, and entirely open to the wind. Very rarely does one see a windbreak in which the idea of side protection is fully carried out. It is not only desirable for protecting the interior of the forest from wind, but to make a real barrier to ground wind, which [2]) may deflect the currents upward sufficiently to make the protection felt for a maximum distance in the lee.

The requirement is simply met. There will be, for example, about 3 rows of the tallest-growing species which can be used, in the center, flanked on each side by about 6 rows of shorter hardwoods and 1 row of still shorter conifers, such as red cedar, ponderosa pine, or blue spruce. The conifers will retain their limbs well down, if lighted on one side. Outside of the conifer rows may be employed the equivalent of 1 or 2 rows of shrubbery. The trees occupy a width of about 100 feet, the shrubbery about 25—30 feet more." . . .

If we understand BATES, the outline of the American "shelterbelts" will be more or less streamline-shaped. In this way the growth of the belt itself will undoubtedly be benefited, as the trees and

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[1]) In the original text this word was spelled "axes". Obviously the author meant "axis".

[2]) At this place in the original text the author wrote "and". We think we may change this into "which".

shrubs will get the greatest protection possible from neighbouring trees. Whether belts with such cross-sections will further answer expectation may be doubted. In our opinion the more the belt will be streamline-shaped the more the width of the sheltered area will be reduced. Here we cannot enter further into this subject, and when treating of the own investigations into the microclimate in the surroundings of windscreens we need not take this argument into consideration again, because these investigations were executed on objects not definitely streamline-shaped.

Now we can proceed to discuss modern investigations into the windfield of windscreens more fully.

In the first place the excellent investigations of FLENSBORG, NØKKENTVED and co-operators (1938 and 1940, see also VAN DER LINDE 1948*b*) should be mentioned. They examined the windfield behind 30 different hedges (1938) and near 24 different forest-borders, as well as in shelterbelt-systems (1940). Moreover, they compared leafed and leafless woodstands (1940). The first publication also contains the text of a lecture by NØKKENTVED on investigations in a windtunnel with models of windscreens composed of slats.

We will deal with NØKKENTVED's lecture first. The models were 5 cm in height. As a result of these experiments it appeared that, apart from some complications, there is a calm immediately behind a completely impervious screen, which undoubtedly will surprise nobody. At a short distance from the screen (8 to 10 times the height of the screen), however, whirls with considerable velocities occur. By making perforations windscreens of various density were obtained. Of course, when the number of perforations increased, the wind movement immediately behind the screen also increased, but at the same time the shelter made itself felt over a greater distance. A screen whose surface had been perforated for 40 to 50 per cent gave the best compromise. At a distance of 30 times the height of the screen the wind velocity measured at $^1/_6$ of the height of the screen even showed a reduction of 45 per cent.

In view of these results it might be expected that concerning the distance over which their influence on wind velocity extends, the densest stands would be of less advantage if compared with moderately dense ones. This appeared indeed to be true in case of windscreens standing in the Danish landscape.

The following examples may serve as illustrations.

A certain 4-m high hawthorn hedge appeared to be an excellent windscreen. Measured at 1½ m above the ground the reduction with respect to the wind velocity in the open was successively at a point h *before* and at points 3 h, 10 h, 15 h, and 20 h *behind* the stand about 24, 62, 60, 42 and 36 per cent (h = height of the stand).

When measurements were made behind an 8-m high spruce hedge of open design these values amounted to ? (not observed), 9, 6, 14 and 1 per cent, while a very dense spruce hedge showed the following picture: 22, 79, 45, 10 and 2 per cent. These numbers clearly illustrate the results obtained by the Danish investigators.

When, however, the results obtained under laboratory conditions in the windtunnel were compared with those gained in the open field, it appeared that the former have given a somewhat too favourable picture of the sheltering influence. It is true the situation in the field was found to be almost the same as that in the tunnel, but in the field the distribution curve of the wind velocities had, so to say, been compressed in a horizontal direction. This fact is of great theoretical importance, because now the wind structure comes into the picture. For it is to be expected that the wind movement in the tunnel will always be of a more laminar character than natural wind, which is always attented with the appearance of turbulence. So it follows that the most favourable lee will be obtained when the wind is of a layered nature, though it is to be admitted that the sheltering objects are not quite comparable.

Thus is has become clear from these investigations in the field that if an adequate windscreen, i.e. one of moderate density is made use of, distinct shelter will be observable in an area with a width of 20 times the height of the screen. Moreover, a narrow strip of ground to windward of the screen is also sheltered.

In this connection an experiment made by Kreutz (1938) is also of importance. In a cabbage field he staked out three dodecagonal pieces of ground with a surface of 120 sqm each. Then he surrounded them with 90-cm high windscreens, consisting respectively of dead branches as generally used for the cultivation of peas, thin gauze and reed mats. The rather pervious fence of dead branches appeared to be the best windscreen. „Sonderbarerweise zeigt also die primitive Reiserhecke die beste Wirkung", Kreutz writes. Seen in the light of Flensborg's results, however, it is easily understood.

Also Nägeli (1943 and 1946, Tanner and Nägeli 1947) made a comparative examination of the windfields of various kinds of windscreens. His work, which was performed in Switzerland, fairly confirmed the results of FLENSBORG, NØKKENTVED and their co-operators, and moreover, added to them. The distribution curves defined by NÄGELI are more exact than those of the Danes, as the former made use of more observation posts. Hence they allow more conclusions.

Generally speaking the lee (measured at a height of 1,4 m) of a windscreen shows the following course. To windward of the screen the influence begins at a distance of 5 to 10 times the height of the screen, and gradually increases in the wind-direction. The wind minimum is not to be found in, but at some distance to leeward of the screen. From this point the protection decreases, till at a distance of about 30 times the height of the screen there is no longer any shelter.

The density of the windscreen influences this picture as follows. In case of a moderately dense screen the wind minimum lies at a distance of 4 h to leeward. The wind velocity may be here about 34 per cent of that in the open. When the density of the hedge is greater also the reduction of the wind velocity in the screen itself will be greater and the wind minimum will be nearer to the screen. Moreover, the wind velocity in the minimum will be smaller (e.g. 14 per cent in case of a very dense hedge), but its increase will take a more rapid course, so that at a distance of 3 h in the case of a dense hedge the wind is already stronger than in the case of a moderately dense one.

Essentially the same distribution occurs in the case of less dense hedges, but naturally the percentages of reduction are smaller, and compared with the moderately dense screen the wind minimum is again shifted a little into the direction of the sheltering object.

The lee at the windward side of the screen appears to be influenced only in a small degree by the density of the screen. The greatest differences do not occur before the wind has entered the screen.

It seems as if all distribution curves converge towards the "point" at 5 h to 10 h before and that at about 30 h behind the stand, but this is not quite certain. It would appear to us that NÄGELI emphasizes this point too much, the more so as its practical importance is only small, because at these "points" the relative wind velocity very *gradually* increases to 100 per cent.

The fact that the wind minimum is to be found not in but to leeward of the stand NÄGELI explains as follows. He points out that the stemregion must be more pervious than that of the crowns. So the air is more or less driven through a narrowing. Therefore the wind velocity must here be proportionally greater. Where the nar-

WOELFLE (1938) hit upon the idea to make use of clouds of smoke for the study of the windfield. This method, if used in the right way, must be called an ideal one. However, up to now few results have been obtained.

For want of measurements, some of the considerations on the vertical component must be based on the distribution of the horizontal component, while others are of a hypothetic nature.

BODROFF (1936) says with respect to the windfield near wind-screens:

"The horizontal and vertical components of the air are changed, the first being decreased while the second is increased. The higher the velocity of the wind in the steppe, the more marked are these changes."

His conclusion: "The vertical changes depend on the density of the shelterbelts. The whirls increase with the density of the belt, . . ." agree with the results obtained by FLENSBORG, NØKKENTVED and co-operators and NÄGELI (see page 25).

NÄGELI (1941) now supposes that there is an "air-cushion" before, in, and behind a windscreen. Owing to the wind-reducing activity of the screen, the air in this cushion moves through the shelterbelt at a reduced speed. For the present we will assume that the vertical section of this cushion perpendicular to the axis of the windscreen is triangular. The apex is to be found near the top of the windscreen, the basis is the ground. The side to windward is steep and the one to leeward shows a slighter inclination. According to NÄGELI at the edge of this cushion, which edge of course cannot be well defined, the free mass of air is going up (to windward) and down (to leeward). In the case of a windscreen of moderate density no turbulence occurs in the region between the two masses of air. This does happen when the screen is too dense.

NÄGELI (1943) further argues that the air-masses which have been pushed up, as they must find a way out somewhere, may be the cause of increased wind velocity in the edge-region of the air-cushion, and therefore also in the next meters above the stand. At the extremity of a stand the same must take place, but now in a lateral direction. This has been proved by him.

It is possible to complete this rude picture with some particulars, if we start from the measurements treated of in the above pages. For this purpose we shall first consider the sheltered area to windward.

As we have said the horizontal wind velocity gradually decreases from the front of the air-cushion, situated at a distance of 5 to 10 h before the screen, into the direction of the wind minimum. Also here this is only possible if everywhere in this part of the cushion an upward movement takes place. The same holds good with regard to the screen which of course stands in this area, and in which, as we know, also a distinct reduction of the wind velocity is to be found. Especially in shelterbelts of great density this reduction is considerable. Also in wider windscreens. such as wood belts or not too extensive woods the vertical component must occur everywhere in the screen (NÄGELI 1943).

The upward air movement is caused by a certain super-pressure in a small area that is situated to windward of and in the stand. These concentrations of air, which of course are only slight, occur because of the fact that part of the air molecules cannot evade through the stand and that other molecules move into the same area as a result of inertia. Moreover, when the air molecules collide with the screen some loss of the kinetic energy of the air occurs, and it is to be expected that some other forms of energy will take its place, i.e. static energy and warmth.

To leeward of the wind minimum, where the wind velocity gradually increases, a descending movement must occur, that is to say, over the whole area above which the increase of the horizontal component is found. So the demarcation lines of the "air-cushion" cannot be drawn exactly. This descending air current to leeward is caused by a slight rarefaction behind the stand.

The investigations made by BATES and STOECKLER (1941, see KITTREDGE 1948) also make a contribution towards the picture of the air-cushion. They measured the wind velocity at various distances from the screen, and at different heights above the surface to far above the screen. First of all these investigations confirm that there is a wind minimum to leeward of the screen, and a strong current of air just over it. The reduction of wind movement near the surface clearly finds expression in their data.

Moreover, it appears that the slant sides of the triangle which for the present we had assumed to be the shape of the cross section of the air-cushion are by no means straight. This is to be seen from the shape of the planes (on cross-section being lines) of equal wind velocities, which for the values 100, 90 and 80 per cent (of the free wind) are considerably deflected into an upward direction near the

For the sake of completeness we also mention here what we learned from literature on the sheltering influences of forest borders. In this respect we meet with various views. Here FLENSBORG and co-operators (1940) and MARCZELL (1926), the latter of whom made measurements in woods in the Hungarian puszta (steppe), have an opinion which differs from WOELFLE's (1939) and NÄGELI's (1946). From the measurements made by the Danes it appears that the forest borders examined by them give protection to adjacent territories over a larger distance than the best hedges or other windbarriers. As usual in measuring the distance the height of the stand was used as a unit. Apparently this effect is caused, they argue, by the circumstance that above the crowns of a forest the air is compelled to move in a horizontal direction. This can never be the case above a territory with hedges. Of course this explanation is supported by the experience obtained by comparing the results in the open with those obtained in the windtunnel (FLENSBORG and NØKKENTVED 1938).

The width (depth) of the forest appeared to be of great influence on the properties of the windfield to leeward. FLENSBORG, NØKKENTVED and co-operators compared the average results of two groups of forests. The first group consisted of woods broader (deeper) than 2000 m and the second of less extensive woods. In the former group the lee extended over a greater distance than in the latter, which was inter alia shown in an almost astonishing way by the situation of the point where to leeward the sheltering influence had been reduced to a value 0. In the former group of woods the distance from this point to the forest border amounted 60 to 70 h, and in the latter group 30 to 40 h. The narrowest wood concerned in these measurement still had a width (depth) of 275 m. The width of the sheltered area found by MARCZELL (1926) was about the same size.

The sheltered area found by WOELFLE (1939) was considerably narrower, while according to NÄGELI (1946) measurements made near Lenzburg in Switzerland, the results of which have not yet been published, would point into the same direction.

NÄGELI attempts to explain these divergent results by pointing out that the wind in the Swiss valleys will be of a considerably more turbulent character than in flat Jutland and in the puszta. As we have already stated some times, the structure of the wind is indeed of great influence on the windfield, in the way supposed by NÄGELI. The results of wind measurements with respect to narrow windbarriers also support this supposition. Among the Danish hedges there are several of which the wind curve to leeward rises considerably less rapidly than in the case of the most favourable windscreen in Switzerland, as we learned from comparison.

In the case of much narrower screens with a width of one or some more rows of trees the difference in width shows itself according to NÄGELI (TANNER and NÄGELI (1941) only by means of their perviousness.

In this survey of literature only passive influences of windbarriers and woods on the windfield have as yet been spoken of. There are, however, also active influences. It is e.g. known that in the daytime there is an air movement at the edge of a forest into the direction of the contiguous field, as a result of the differences in temperature in the lowermost air layers.

HERR (1936) and DÖRFFEL (1935) have indeed found such a wind. It is a very light wind that may be recognised by means of its property to convey cool humid air.

Moreover, there is a nocturnal forest wind, which arises from the cold air streaming down from the crowns of the trees towards the field. KOCH (1934, GEIGER 1942) mentions in this connection a velocity of 1 m per second.

These active influences have been discovered near the borders of stands of considerable extent. Nevertheless these influences are only small. It is to be expected that in the case of smaller strips of wood they will be even smaller, owing to which they will sink into insignificance beside the effects of passive influence. However, under favourable circumstances (undisturbed incoming and outgoing radiation and calm weather) they may from time to time be perceivable.

It will seldom happen that in a territory one isolated hedge is to be found.

Therefore the question immediately arises what the influence exercised by the windscreens collectively, will be. Measurements with respect to this problem have also been made, namely by FLENSBORG, NØKKENTVED and co-operators (1940) and by NÄGELI (1943 and 1946). Moreover, FLENSBORG and NØKKENTVED made measurements on the basis of models.

In the first place attention should be paid to the latter. In these investigations small 5-cm high screens were used and measurements to dense screens. This, however, cannot be decided upon with certainty, as the distribution curves of these single screens are not known. It seems probable that there was cumulation of influences, although it was difficult to recognize it as such.

Further, there is a second collective influence of screens, but it is of quite a different nature, as this effect brings about a reduction of the "free wind" itself.

A territory with hedges which is extensive enough represents a "rough surface", which offers more resistance to the air than a "smooth" one, i.e. a territory without trees.

In this connection some results obtained by BRAAK (1929) should be mentioned. He examined the distribution of the average wind velocity above the Netherlands and adjacent territories, on the basis of data obtained at various stations of the Royal Netherlands Meteorological Institute (K.N.M.I.). These data refer to a height of 6 m. Here we shall only enter into his views of the westerly wind. Amongst other things he writes as follows:

"A narrow sheltered region is situated on the landside of the dunes, more eastward, however, the effect of the southwesterly seawind, as demonstrated by the one-sided growth of the trees, is observed everywhere in the bare flat plains of Sealand, South- and North Holland and Frisia, decreasing gradually with the distance to the coast.

A reciprocal action between wind and tree-growth is here in operation, the wind hampering the tree-growth while the absence of trees implies an increase of wind velocity. Therefore, it may be assumed that in the eastern provinces not only the greater distance from the sea, but also the vegetation brings about a decrease of windforce.

Generally speaking, the greater friction above the land may be considered as the principal cause of the diminution of wind velocity in the interior.

The decrease of windforce towards the interior is most rapid near the coast and gradually diminishes at a greater distance. At 50 km from the sea it has become so small, that it cannot be distinguished with certainty from local effects. We find almost the same average wind velocity in a region that extends from De Bilt over North Germany to Berlin, the differences being controlled more by the local conditions than by the distance from the sea."

In this quotation three points are important for us: the narrow sheltered region east of the dunes, the gradual decrease of wind velocity towards the interior and the equal distribution of wind velocity between De Bilt and Berlin.

Of course we must not consider the dunes as a windscreen or a system of screens in the sense of the preceding pages. Here we are concerned with a real rough surface which on an average rises to a height of some ten meters above its surroundigs. On the seaside the wind above the beach and the exterior dunes will be pushed up and then will meet with the resistance caused by the rough surface. That a sheltered region is brought about on the landside of the dunes is easily understood. BRAAK did not have enough data at his disposal to be able to give some more information on the width of this area.

The gradual diminution further to the east shows cumulation of the effects caused by the obstructions the wind meets on its way, and the constant average between De Bilt and Berlin indicates a state of balance. That there is a discontinuity between the proverbially flat and bare Dutch polderland from the coast to De Bilt and the wooded part of the country east of De Bilt is, in this connection, quite irrelevant.

On the strength of the results obtained by BRAAK it is to be expected that also a region with windscreens will influence the "free wind" perceivably, provided the area is extensive enough. Also here a gradual decrease in wind velocity will occur. As the resistance in such a territory will be much stronger than in the flat Dutch polderland, it seems likely that the state of balance will be reached sooner than in the case treated by BRAAK.

We have already seen that we are here concerned with a reduction of the "free wind". A single screen will behave in this free wind in the way discussed above, and will moreover contribute to the reduction of the free wind.

It seems probable that above such a region the air is somewhat pushed up, so that the wind, in about the same way as when it meets a hill, will be inclined to flow round it and over it at a greater height.

In dry hot regions of America (BATES 1934) and Russia (BUCHHOLZ 1941, MAYER-WEGELIN 1943, ZON 1949 and an anonymous article in the magazine "U.S.S.R. in Reconstruction", no. 3, 1949) huge afforestations are being made, in order to raise the yield of agriculture in these regions. That indeed much good is to be expected from this comprehensive plan is demonstrated by the figures of produce recorded by NÄGELI (1941). The American plan makes provision for the laying-out of a belt of 1800 km long, on an average 160 km wide, running from north to south, in which the cultural soil is to be protected by windscreens. In Russia the plan comprises the whole of the Russian steppe in Europe. Here a network of shelterbelts is to protect the crops against desiccation, and belts of forests, chiefly running from north to south are to be planted. The most easterly will have a breadth of 100 km, and will extend along the river Ural. This belt "will take the first assault of the scorching desert winds".

WOELFLE (1938) made a plan for local application. Also in this one broader strips of woodland (50 m wide) were included as well as narrow hedges.

3. PRECIPITATION

Little is known of the influence of windscreens on precipitation. The first important question that presents itself concerns the influence on the total amount, and the answers given differ from each other.

NÄGELI (1941) records measurements made at the experiment station in the Kamennaya steppe. The results seem to indicate that in sheltered areas more precipitation occurs than in unsheltered ones, as between the years 1918 and 1924 the annual precipitation in the former amounted to 15 per cent more than in the latter. Others, however, severely criticized the methods used in making these measurements, NÄGELI mentions.

That also snowfall is influenced by windscreens is clear to every close observer. When snow is falling during strong wind and at temperatures below zero it is to be observed that most snow lies in sheltered places, and in such a manner that the depth of the layer of snow is a reflection of the windfield (KREUTZ 1943, NÄGELI 1946, see also page 20). In the open the snow is swept on, until it settles in a sheltered place, e.g. in a trench or near a cluster of trees or a house. In the annual averages of the Kamennaya steppe the figures on snowfall will undoubtedly have been worked in. So the increase in precipitation mentioned above does not say anything of the amount of rain fallen, if we do not know the proportion of the annual amount of snow to that of rain.

Of course the statements of KREUTZ (1941) and NÄGELI (1946) according to which "the depth of the layer of snow is a reflection of the windfield" holds good as long as the depth of the snow layer is small in relation to the heights of the lee giving objects. In case of heavy snowfall, however, snow dunes may influence the windfield in a considerable measure.

During severe winters a thick snow layer may be an advantage to winter cereals. Therefore a sheltered area is in this case to prefer to an open plain (NÄGELI 1941). The large quantity of run-off when the snow melts may under certain conditions also be useful.

The influence of wind on rainfall found by GEIGER (1927, 1928 and 1929, GEIGER 1942) should be mentioned here. He determined the rainfall in the windfield of a hill. He found the precipitation, measured by means of rain gauges placed horizontally, was greatest on the lee side, which result is in contrast with those obtained in measurements near mountains, where, owing to the cooling down of the upward movement, rain will fall on the wind side. GEIGER considered his result to be self-evident, as in strong wind part of the rain is swept along in a horizontal direction, owing to which most rain must fall in sheltered places (just as in the case of snow).

If we should apply GEIGER's results to regions protected by means of windscreens, in which, as we have seen, places with different wind force are to be found at a short distance from each other, we may expect that also here differences in rainfall will occur. Some rather incidental rain measurements made by KREUTZ (1943) seem to confirm this surmise. These considerations, however, do not allow a conclusion referring to sheltered regions of greater extent, as in this case various other factors will play a part.

4. TEMPERATURE

Literature on our subject also contains interesting information on the temperature in sheltered areas. For us this is of great importance, the more so as temperature is the factor which we ourselves have studied most minutely.

In Russia the average summer temperature is between windscreens somewhat lower, the average winter temperature a little higher than in the open steppe. The differences, however, are slight (NÄGELI 1941).

According to FLENSBORG (1926) windscreens increase the average air temperature. His opinion is probably based on the results of an investigation by LA COUR (1872, NÄGELI 1941) in Denmark. According to the latter, protection distinctly causes higher temperatures in the daytime, somewhat lower temperatures, however, at night.

3

The cooling down of the sheltered area with respect to the unsheltered one will continue as long as the balance of heat is negative, in other words till sunrise of the next day, if no complications occur. Therefore, in a sheltered area the danger of nightfrost will be greater than in an unsheltered one.

According to BODROFF the differences in temperature that may arise in the daytime amount to 6 or 7° C on hot days.

The above considerations contain that which in our opinion are the purports of BODROFF's statement, with some of its consequences. This argumentation is completely based on the lee-producing influence of shelterbelts. Other effects that might influence the temperature of the air have not been taken into consideration. It is not clear from BODROFF's publication on what facts his conclusions are based. Probably, however, he had at his disposal series of observations made during a period of sufficient length. Thus it seems most probable that we are to consider the passage quoted as an attempt to formulate a microclimatic law. One may look upon BODROFF's ideas as a specification of those of LA COUR (see page 34).

Only few facts are known with respect to the temperature of the ground in sheltered areas. BERNBECK's investigation (NÄGELI 1941) makes us presume that owing to the shelter a distinct increase in soil temperature will generally be obtained.

Also in the experiment made by KREUTZ (1938), and described in the section on the influence of woodstands on the wind (see page 18), a positive influence of the shelter over the soil temperature was observed.

BATES (1911) observed the influence of the shade of screens on the temperature of the soil measured at a depth of 50 cm. In one case he observed a temperature under trees which was nearly 3½° C lower than the temperature in the open. Further this investigator found that the influence of windscreens over the soil temperature measured at this same depth is not the same in all seasons. During increasing declination of the sun, i.e. in spring, the value of this quantity was greater in the sheltered area, during decreasing declination, i.e. in autumn, it was lower, a phenomenon that of course must be closely related to that regarding the diurnal course of the air temperature mentioned by BODROFF. The differences observed, however, were small. Generally speaking they were smaller than 1° C and mostly even only a fraction of it.

Except for the shading influence, which has already been concisely discussed, all other influences of windscreens on temperature that have already been treated are of an indirect nature. Also direct influences ought to be dealt with. They are the result of radiation on the sunside of the stand and of the shade on the other side. In this connection the orientation of the stand plays an important part.

Observations made by HEIDEMA (1923) and SCHMOOK (1928) indicated the existence of a belt with extra high temperatures to the south of sheltering objects in sunny weather. They based this conclusion on injure done to various kinds of vegetations. In this connection they spoke of reflection of heat against the stand. Indeed, reflected solar energy will play a part here, but another part is played by the energy re-emitted by the stand.

The more energy the side of the stand receives, the stronger the effect will be. In this connection the work by SCHUBERT (1928, GEIGER 1942) is important. The latter calculated for a clear day in the middle of May the radiation into the horizontal plane and that on walls with northern, eastern, southern and western aspects at Potsdam (in lat. 52½° N). He found respectively the following values: 547, 39, 278, 264 and 278 g. cal/cm² per day. From this it appears that a wall with southern aspect is at this time of the year somewhat inferior to walls fronting east or west. In winter a wall fronting south, however, has a great advantage over others, as a result of the low sun's altitude.

Especially in the latter case, i.e. in the daytime in winter and early in the morning and late in the afternoon in summer, we may therefore expect rises in temperature on the sunside of the stands. In this connection, however, we should remember that the sides of stands do not form closed walls, especially in winter, and that therefore only part of the solar energy will be caught up, especially if the screen is not a very dense one.

The regular companion of reflection of solar energy on the sunside is the shade on the opposite side of the windscreen. Shading is caused by the interception of direct radiation. Of course there is also partial interception of diffuse radiation on either side of the stands.

GEIGER (1935) has worked out the width of the shadow with regard to objects situated in the geographic latitude of München (48° N). He gives diagrams from which the course of the width of the shadow throughout the day can be read for mid-summer, mid-winter and the equinoxes. VAN DER LINDE and WOUDENBERG (1946 have

6. Evaporation

Evaporation is of great importance to the living plant. Bodroff (1936), supporting himself on his experiences in the dry Russian steppes, considers evaporation to be the best criterion for the efficiency of windscreens, as it is the factor which indicates the degree of dryness of a climate.

As evaporation depends on wind velocity, relative air humidity and temperature, and all these factors, as appears from the preceding, are controlled, in a measure, by the screens, it is clear that the latter will also influence evaporation, which is confirmed by the facts. The results obtained by La Cour (1872) already showed that there is an influence of woodstands on evaporation. He found a distinct decrease of this factor both to leeward and to windward of the screens. As his measurements, as appears from the figures borrowed by Nägeli (1941), cannot have been very exact we shall not take them into further consideration.

When in a given area temperature and relative air humidity are distributed equally enough, differences in the evaporation values will be controlled almost exclusively by the wind, and in this case there will be much resemblance between the distribution of evaporation and that of wind velocity. In most cases this has appeared to be true. Nice examples of it were given by Bates (1911) and Nägeli (1943). As an illustration we quote here in the first place one of Bates' conclusions. "The distance from the windbreak to the area of greatest protection [from desiccation] depends upon the position of the mass of foliage which affords the protection. With a dense grove, it is immediately in the lee of the trees; with a narrow belt of trees that lack lower branches, it may be as far from the trees as five times their height and it moves outward as the velocity of the wind increases." Except for the last sentence the description fits in with Nägeli's views of the windfield behind screens of different densities.

Nägeli (1943) made evaporation measurements simultaneously with part of his wind measurements and at the same height (1,4 m). He found a striking correlation to the wind velocity. By means of these data he could confirm Woelfle's conclusion, according to which evaporation is about proportional to the square root of the wind velocity (when all other conditions are the same). Yet in some places Nägeli's evaporation curve differed from his wind velocity curve. For example, the wind minimum lay somewhat to leeward of the stand, i.e. outside it, as we have stated some times, whereas the evaporation minimum always lay in the stand. NÄGELI's reasoning runs as follows: Great differences in temperature and air humidity were not observed. The only factor that showed a jump from the stand to the adjacent territory was radiation and herewith the situation may be clear.

The last of BATES' conclusions to be quoted contains some points, which have been mentioned when we discussed the constancy of the percentage of shelter in various wind velocities. This conclusion runs as follows: "If a windbreak is dense enough to resist the strongest wind, the protection which it gives to any point in its lee increases with an increase in wind velocity. In the case of a moderately dense windbreak, the efficiency remains about the same under all conditions, because the leakage through the windbreak is about the same proportion of the total amount of wind. With a very open windbreak the efficiency decreases with an increase in wind velocity."

BODROFF (1936) writes as follows: "The influence of stands on evaporation extends over a distance which, in wind velocities of 2,5 to 3 m/sec in the open exceeds 60 times the height of the windscreen, and which amounts to 100 times the height of the screen in wind velocities of 5—10 m/sec." With regard to the percentage of shelter in various wind velocities in relation to evaporation we find in BODROFF's statement the same ideas as in BATES' mentioned above. We need not enter further into this question since the distribution of evaporation as we have learned is in most cases closely related to the distribution of wind velocity, and the latter has been so amply discussed, that in this place we may refer to the section on wind.

About the 60—100-h wide zone which, according to BODROFF, showed protection with regard to evaporation we can only say that these values seem rather high, when compared with those obtained by the greater part of the other investigators.

Especially much variation exists, as to the height of the shrubs, as they are cut every 8 or 9 years, when they are about 5 m high. The stumps are not removed, however, so that in the next spring they will bud again.

Of course the exploitation of the belts influences the micro-climate. If in some part of the region the shrubs had recently been cut, this part could not be used for the investigations. However, a suitable area could always be found.

The map (fig. 3) distinctly shows that the width of the space between the strips of oak-coppice as a rule did not exceed 50 m, and often the distance between the stands was considerably smaller. If we now apply what the literature treated of above has taught us with respect to such situations (FLENSBORG, NØKKENTVED and co-operators 1940, NÄGELI 1946, TANNER and NÄGELI 1947), for the present assuming that oak-coppice belts are among the screens of moderate density, we find that in SW and NE winds nearly every part of the territory between the belts is sheltered to a certain degree, if the belts have reached a height of 50/25 m = 2 m.

It is, however, probable that the belts are denser than those of the "right" type (see page 138). Therefore the distance from one belt to the other should be smaller than 25 h if the area will satisfy the condition mentioned above. The investigations were, however, always made in parts of the area where the stands were considerably higher than 2 m, and during some periods of the observations the cross-sections examined were considerably shorter than 50 m. Therefore we may assume that, when the wind direction was perpendicular to the stands, not a single point of the cross-sections examined was exposed to the windforce in the open. Of course this does not exclude the possibility that the usual differences in windforce occurred along the cross-sections.

The belts are planted with oak-coppice (*Quercus Robur* L.), among which in some cases alders (*Alnus incana Mönch*) are found. In the long run, however, various kinds of other shrubs will appear in the original plantation. The soil under the belts has a cover of herbs, and over long distances the sides are overgrown with blackberry-bushes (*Rubus spec.*) and other low shrubs. By way of illustration we give the floral composition of the shrub story as far as the belts indicated on the map as I and III are concerned (see table below).

The percentages indicated should be considered to denote what part of the surface of the belt is taken up by a certain species.

The climbers blackberry, honeysuckle and hop are indicated as follows: 0 = not found; 1 = found in limited numbers; 2 = found in moderate numbers.

COMPOSITION OF WOODSTANDS I AND III

	I	III
Shrubs:		
Common oak *(Quercus Robur L.)*	65,8%	72,4%
Speckled alder *(Alnus incana Mönch)*	—	9,1
Birch *(Betula verrucosa Ehrh.)*	9,2	4,2
Buckthorn *(Frangula Alnus Mill.)*	7,2	6,9
Mountain ash *(Sorbus aucuparia L.)*	7,3	4,4
Shadbush *(Amelanchier laevis Wieg.)*	2,6	1,8
Bird cherry (*Prunus Padus L.*)	5,8	0,2
Cherry *(Prunus Cerasus L.)*	—	0,4
Willow *(Salix spec.)*	1,0	1,2
Apple *(Pirus Malus L.)*	1,0	—
Climbers:		
Blackberry *(Rubus spec.)*	2	1
Honeysuckle *(Lonicera Periclymenum L.)*	2	1
Hop *(Humulus Lupulus L.)*	0	2

The other stands in the area are of a similar composition.

In one part of the region nearly all stands have been uprooted, because of which there is an open plain (see fig. 5 on plate II). All other conditions however, have remained the same as in the areas in which the belts have been preserved.

The belt indicated on the map as nr. IV had just been cut down to the ground at the beginning of the investigations (1943), so that the station "open area" (see the chapter on method and technics) was situated in the middle of an extensive plain. Neither could this belt disturb the observations made at this station when later on the shrubs had grown up again, as the distance to it was large enough.

We ought to draw our attention to another peculiarity of the region where the investigations were made which is of a climatic nature. As already stated above, Oldebroek is situated on the northern edge of the Veluwe. The latter is bordered here by the IJssel Lake (the former Zuider Zee) and the coastline runs on an case of high crops one is obliged to make one's way through it, leading towards or along the various instrument stands. Also this path may cause all kinds of disturbances.

We have always endeavoured to eliminate these disturbing influences as much as possible. For this reason the measurements have alwasy been made above the same kind of crop in both areas.

In the case of low crops, as e.g. young rye or low turnips the making of the arrangement presented practically no difficulties. The instruments could be easily placed in or at a small height above the crop. The influence of the crop and the disturbance caused by the path that inevitably had to be made (along which the crop had to be trodden down) must have been rather small, so that the influence of the stands must predominate.

We have hesitated long before beginning to make measurements in full-grown or half-grown cereals. That's why in the late spring and in the early summer we were always compelled to look for places where the crops were still low. Therefore rye-fields were the first to be excluded from our investigation. When at last we ventured to examine also fields of high cereals we obtained results we could not square with those obtained during other periods, so that we had to assume that close to the ground the influence of the stands is completely predominated by the microclimatic properties of the crop and of the narrow path. For this reason the data obtained in the high rye (May 1946) could not be taken into further consideration. In order to eliminate the various causes of disturbances as much as possible, the most important observations in a later period at this time of the year (July 1947) were made at the level of the ears. In the report on this period we only state the results of wind and air humidity measurements. Concerning the temperature we must remark that in one period of activity we have not been able to succeed in obtaining a satisfactory insight into the microclimatic situation under the conditions mentioned.

The measurements were made during short periods, of some days each. It was tried to get as complete a picture of the daily course of the various microclimatic factors in the two areas as was possible. Along with the measurements all changes in the weather conditions were noted down; these data were afterwards completed with those obtained by observations made at De Bilt.

Fig. 2. Hedges in the experiment area (sheltered area) in June 1950 photographed from the roof of a car.

Fig. 4. The landscape in the sheltered area. Full-grown hedges to the right and to the left. In the middle a cut-down specimen. In the back-ground the oak planting along the road parallel to the diagonal of fig. 3.

Fig. 5. The open area in June 1950 taken from the roof of a car.

Owing to the black-out during the war and the small number of assistants that was available it has not been possible to make observations at night. Also after the war observations were only made in the daytime and in the evening. Thus our data on the hours of the night are chiefly restricted to the indications of minimum temperatures obtained by the Six-thermometers.

The data obtained in the experiment area were considered with respect to the prevailing weather conditions and the time of the day. Therefore the investigation was rather of a micrometeorological than of a microclimatic nature.

As a matter of course the distribution of shade also played a part in these considerations.

The data on the weather conditions supplied by the K.N.M.I. had to be considered with some reserve, as the experiment area of Oldebroek is situated at a distance of 60 km from De Bilt. That this was necessary has already been explained in the description of the region in which the investigations were made.

As much as possible readings in the two areas should be made at exactly the same time, in order to obtain data that may be compared with one another. When the weather conditions show a regular course, that is to say when there are only small changes, in the middle of the day, it does not matter very much if some time elapses between the readings in the two areas. When, however, the weather conditions are variable the measurements should be made to synchronize as much as possible.

With regard to the data obtained in the first periods of the investigation such differences in time do exist. When comparing these data with each other this should be remembered. Later on, when we availed ourselves of a field-telephone this difference in time could, but for some seconds, be avoided.

But even if the observations are made at exactly the same time, it is not always quite certain that the data are comparable as at any moment there may be a difference with respect to the insolation of either area. Also this factor was taken into account when the data were interpreted.

Occasionally it has been necessary to interpolate between two series of observation, in order to make comparison possible. In most cases this was caused by the fact that for some time only one observer for both areas did the work.

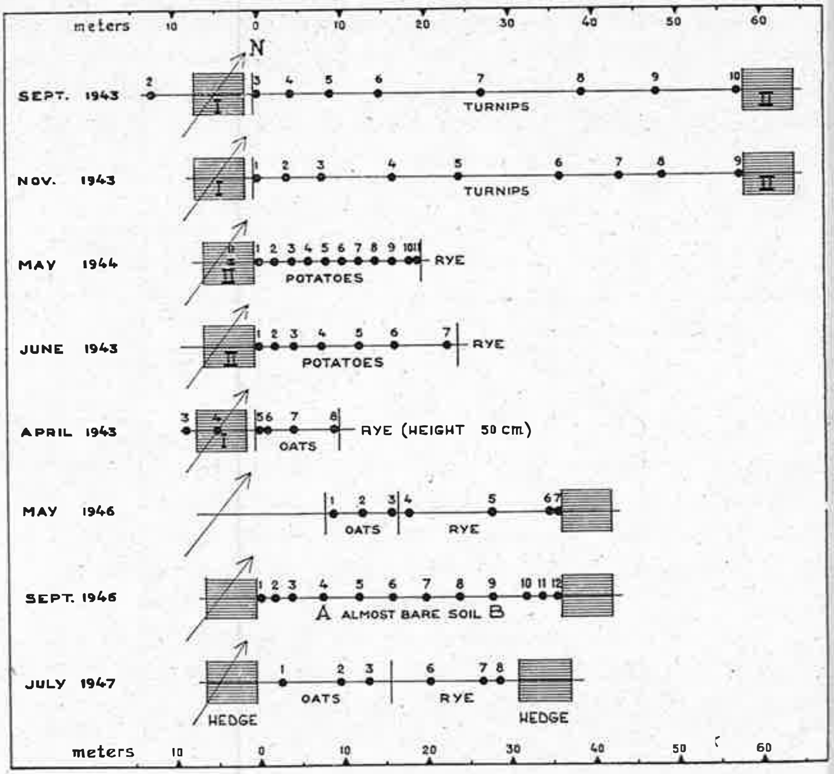

Fig. 6. Arrangements in the sheltered area in the different observation periods.

Thus in all cases two microclimatic arrangements had to be made; one in the sheltered area, another in the open. We do not give here a detailed description of the arrangements that were used, but it is given along with the data of the various periods of observation, while a survey of the arrangements in the sheltered area is given in fig. 6.

Here we give a survey of the microclimatic factors that were studied, and of the instruments used. Moreover the latter are shown in fig. 7 on plate III.

Wind. Although the distribution of wind velocity and direction in the landscape is of primary importance for the nature of the microclimate, only little attention has been paid to this subject, as we had not enough instruments at our disposal, and as the other observations asked too much of our time.

During some periods we could avail ourselves of two portable cup-anemometers and sometimes we made use of some self-registering apparatus. With these instruments it was not possible to make a series of observations within a short time, as was required for this investigation because of eventual changes in wind direction. The few results mentioned are only given by way of orientation.

Shading. The shading was determined by means of the graphic method (VAN DER LINDE and WOUDENBERG 1946).

Temperature. Most attention was paid to the distribution of temperature in the two areas. This was in the first place necessary because of this microclimatic element itself as a growing factor for the vegetation, while moreover temperature generally is a criterion by means of which an insight may be obtained into the causes of the distribution of the various gradations of the microclimate in the region investigated.

In determining the temperature SIX-thermometers were chiefly made use of, as they have the important advantage to indicate the nocturnal minimum temperature, which is so important for plant life. In order to check the measurements made by means of these instruments some very good mercury thermometers were later on also used.

The thermometers were always placed in white painted boxes, made of eternite, to reduce as much as possible errors caused by radiation (fig. 8 on plate III). These boxes consist of three horizontal small plates, fastened to each other at the four corners by means of long screws. The upper plate has a size of 14 × 14 cm, the two others of 12 × 12 cm. Between the upper and the middle plate is a distance of about 2 cm. The thermometer is to be mounted in such a way that the bulb finds its place in the space between the middle and the lowermost plate. The distance between the two latter plates is 3,5–4 cm. Two opposite sides of the box are provided with narrow plates, placed in a vertical position and in such a way that the wind can freely approach the reservoir, and that at the same time the sun cannot shine on it. In view of this the boxes should always be placed in such a way that the plates on the two sides are turned to east and west.

During the first period these boxes were simply put on the ground. In doing so the reservoir of the thermometer was situated at a height of 2 cm above the ground. Later on it was thought better to put them at a height of 10 cm by means of little wooden blocks, in order to get in some degree out of the layer with very great differences in temperature immediately above the ground, and to avoid a possibly disturbing influence of some unevenness of the ground or the crop as much as possible. Yet the observations made at 2 cm have supplied us with many comprehensible data, so that it may be assumed that also these observations are sufficiently reliable in many cases. Also the indications of the dry bulb of the ASSMANN-psychrometer which as a rule was placed at 30 cm, sometimes supplied valuable data.

When temperature measurements of the lowermost air layers are discussed, it should be remembered that we are here concerned with the determination of the average values of an element that is liable to rather important fluctuations. The fluctuations, which are a result of convection and turbulence, follow each other so quickly, however, that an ordinary thermometer, and especially a SIX-thermometer with its rather considerable bulb and a high specific heat, cannot register them. Thus a thermometer gives an average value, and our reasoning starts from these average values, which we indicate as "the temperature" at a height of 2 or of 10 cm above the ground. Of course the fluctuations in the temperature we are speaking about are strongest in the middle of the day, when the convective movement and likewise turbulence are strongest.

In the meteorological screens which were used in some of the later periods of observation always thermographs, hygrographs, SIX-thermometers and a fixed psychrometer with a dry and a wet bulb thermometer were established.

These screens were not placed at the usual height of 2 m. Their bottoms were only 40 cm above the surface.

Evaporation. By evaporation we understand the loss of water on the surface of an instrument which had been moistened on purpose (evaporation gauge).

Beside temperature, evaporation is also a very important factor for the crops, as it is a measure for the combined influence of wind and the saturation deficit of the air. It is also an important factor with respect to the problem of shifting soils.

Although evaporation is a complex factor, depending on wind, air humidity and temperature, we decided to bring it into our investigation, the more so as among the factors examined we had already to do without the wind. Moreover, it is rather easy to make evaporation measurements, and they do not take up much time.

The evaporation gauges made use of were of the PICHE-type, as described by REITHAMER (1873), however, simplified. They consist of an about 15 cm long glass gauge, placed vertically, and being closed at the top. This gauge has a graduation in cc and is to be filled with water. The lower side is closed by means of a circular piece of stiff blotting-paper with a small hole in it in order to allow the air to enter into the gauge. The evaporating surface was situated at 10 cm above the ground, which, in the case of a low crop, was thought sufficient to guarantee the necessary air circulation. It is to be understood that one is not allowed to make very high demands as to the exactness of the results obtained with these instruments.

In contrast with the other instruments the evaporation gauges were read only twice a day, namely along with the first and the last observation series of a day.

The evaporation gauges were not used if night-frost might be expected, because of the danger of damage to the tiny instruments.

Of course no absolute value may be attached to the data of evaporation gauges, as the nature and the colour of the evaporating surface, and the way in which the surface is moistened influence the amount of water that evaporates during the unit of time in a high degree. Therefore only the results obtained by evaporation gauges of the same type may be compared with each other.

The evaporation determined in this way is not in all respects parallel to the amount of water evaporated by the plants and the soil, as living plants regulate their evaporation by means of pores (LUNDEGÅRDH 1930).

Air humidity. For the determination of air humidity we made in the first place use of psychrometers of the type constructed by ASSMANN. They were always placed in such a way that the inlets were at 30 cm above the ground.

Hygrographs and fixed psychrometers with a dry and a wet bulb were placed in the meteorological screens, in the few cases that the latter were used.

An observation made by means of the ASSMANN-psychrometer always consisted of 10 pairs of readings. Owing to this fact these observations took rather much time, so that there was a rather great

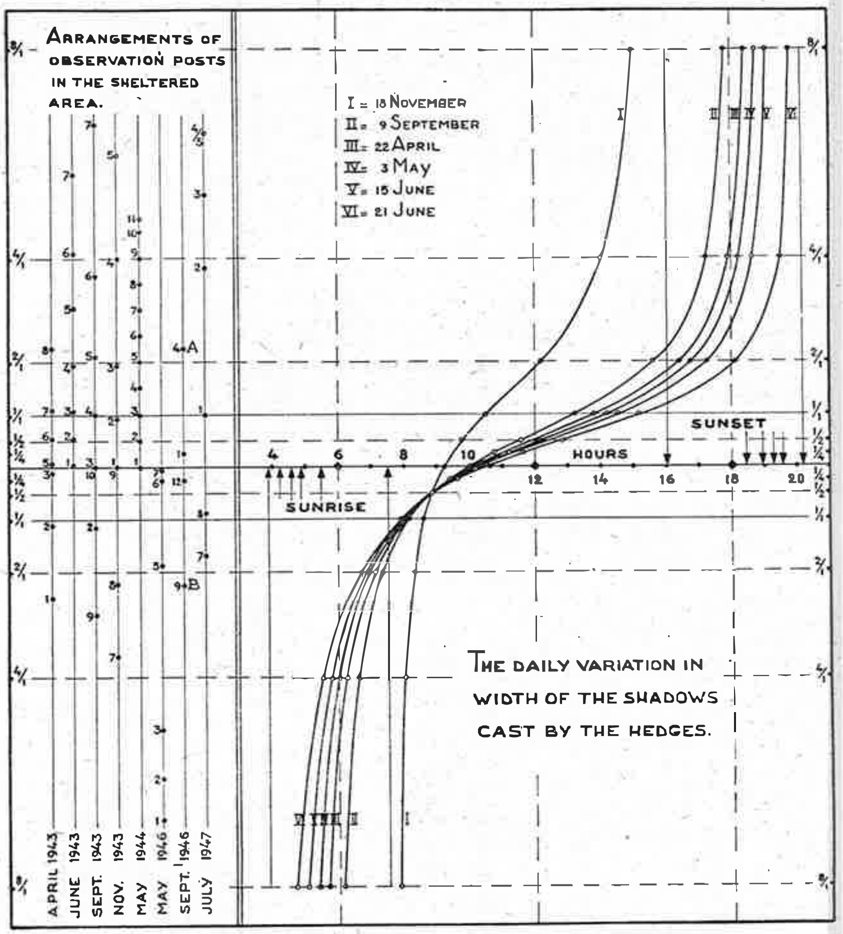

Fig. 9. The daily variation in width of the shadows cast by the hedges during some days of the year.

In the left part of the diagram a survey is given of the distributions of the observation posts in the sheltered area during the various periods. This survey is not simply a copy of fig. 6, because in this case the distances between the various posts and the stands had to be expressed in the heights of the stands. These heights were not always the same.

As has been said above the method for the determination of the width of the shadow (Van der Linde and Woudenberg 1946) is only exact if the windscreen ("sun"screen) is a perfectly regular one. The results obtained, however, have in most cases appeared to be fairly reliable.

Of course one can also read from these diagrams which side of the stand was exposed to the sun, and which not.

B. Local Weather Survey

In the evening of *September 7* there was a light west-wind (0), and a moderately dense cloud deck (Cs + Ci + As; $^{6}/_{10}$).

Also during the following *night* the wind velocity was small. The cloud deck consisted of Cs + As, while a considerable dew was falling.

Early in the morning of *September 8* a light wind (1) was blowing from SE. Soon it increased a little (10^{37} force 2) and veered to WNW. In the afternoon the wind was WNW 3.

In the forenoon there was much cloudiness at a great height (8^{15}; much Ci + Cs, in the distance also As and Ac; $^{8}/_{10}$). At first the sun was shining faintly through the thin veil of clouds which was getting denser and denser, so that already at 10^{04} the sun became invisible. At 10^{43} the sky was for $^{9}/_{10}$ covered with Ac + As + fn. At about 12^{30} cloudiness decreased, and after a shower (13^{10}; Cb + Cu + Ci + Ac; $^{5}/_{10}$) had brought some rain, the sky was clearing. Thus the afternoon was rather sunny. At first there were still some Cu and later also some Ac and some small Ci. In the evening the sky was all but clear.

The *night* was clear, while early in the morning of *September 9* there was a light fog close to the ground, the sky being clear. A considerable dew had fallen. In the morning there was at first a light wind (8^{19}; 2) from ENE. At 9^{56} the wind appeared to have turned to ESE and at 11^{14} it had somewhat increased (3). All day the wind remained easterly and during the afternoon it again increased a little.

After the fog had lifted, the whole forenoon was sunny with only some small Cu and Ci. After noon the amount of cumuliform clouds increased (12^{50}; some bigger Cu + Cu hum and 13^{10}; many big Cu; $^{4}/_{10}$). These clouds soon disappeared, being replaced by a Ci-screen (14^{10}). The weather remained rather sunny. Also in the evening there were many Ci-clouds (18^{15}; $^{5}/_{10}$).

According to observations made at De Bilt the wind on September 7 and 8 was moderate, its maximum velocity not exceeding 8 m/sec. Its direction was very variable. On September 9 the wind was somewhat stronger (in the third six hours' period the maximum was from 11 to 12 m/sec), and was blowing from between NNE and E. In the first two nights (7—8 and 8—9 September) there was little wind (maximum not above 4 m/sec), in the third night, however, it was somewhat stronger (maximum 10 m/sec). Also in the morning of September 10 the wind was still moderate (ENE).

Relative air humidity was rather constant during the whole period, being 70 to 75 per cent.

Generally speaking, the air temperature was somewhat above normal.

If we compare the weather data of Oldebroek with those of De Bilt our attention is drawn by the fact that on September 8 the wind directions were not the same. The circumstance that at Oldebroek in the morning the wind turned from SE to WNW indicates that we are here concerned with the influence of the IJsselmeer (IJssel Lake) (Zuider Zee-effect). Indeed the weather conditions were such that this effect must be noticeable.

C. The Data

a. Temperature at a Height of 2 cm (See fig. 10 a, b and c, 11 and 12)

In the first place it should be noticed that only exceptionally the same temperatures were found at the two posts in the open (8.11^{10} and 9.6^{22}). Generally the lower part of the field (post II) had the higher temperature throughout the day. In the evening, during the night and early in the morning the situation was usually reversed. This situation may be called normal for the weather conditions under which we worked. The greatest difference observed was 1,4° C (8.14^{17}). As was to be expected, the lower part of the field was then warmer than the higher.

During the night from 9—10 September the minimum temperatures at the posts in the open were equivalent or all but equivalent to each other, which was in contrast with the situation of the two nights before. This was probably caused by the relatively strong wind during the last night.

It seems probable that with this arrangement and under these weather conditions the highest and the lowest value of the momentary temperature range in the open were approximated. Therefore we may compare these values found in the sheltered area with those found at the two posts in the open.

In the sheltered area the differences in temperature between the posts were greater than in the open. This was especially shown with high sun's altitude and under uncovered sky, i.e. with strong

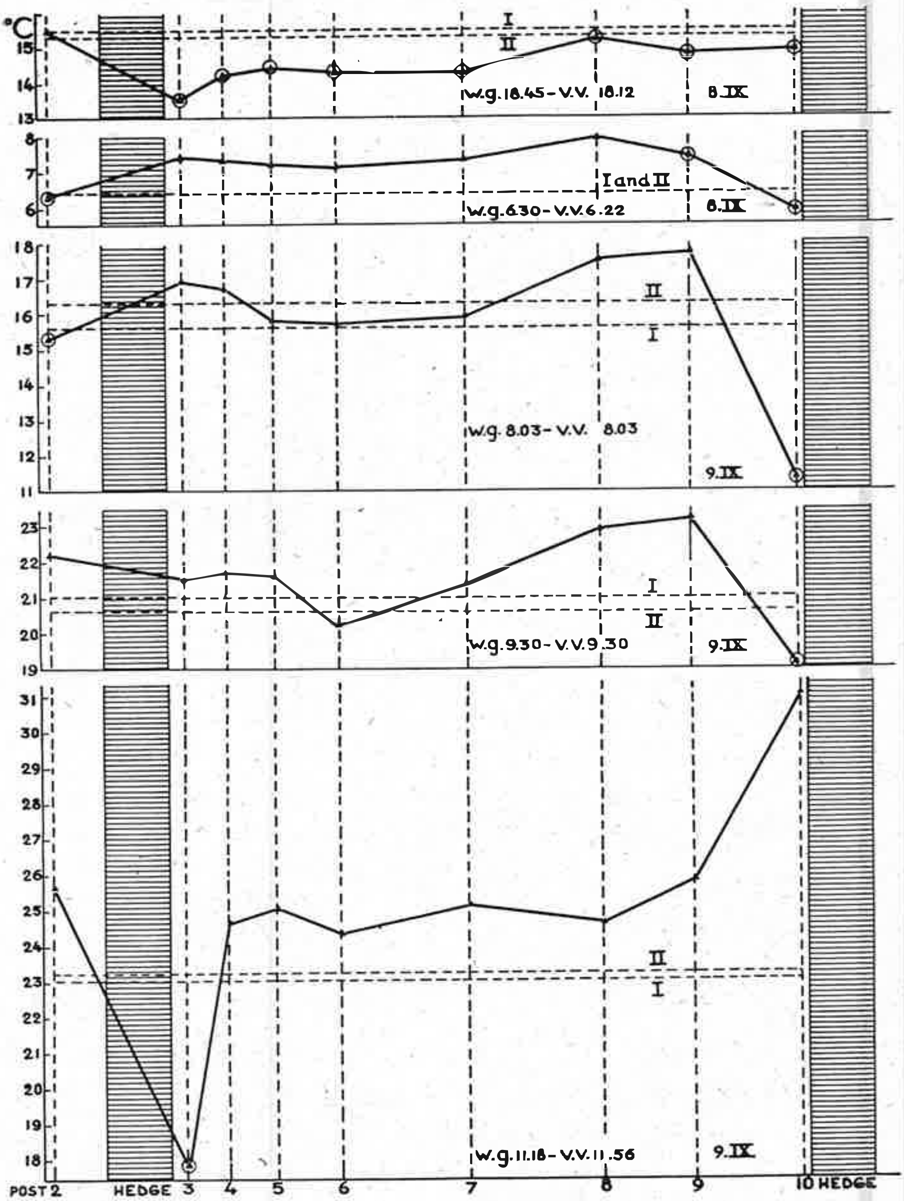

Fig. 10b. Temperature at 2 cm during the period of September 1943 (continuation).

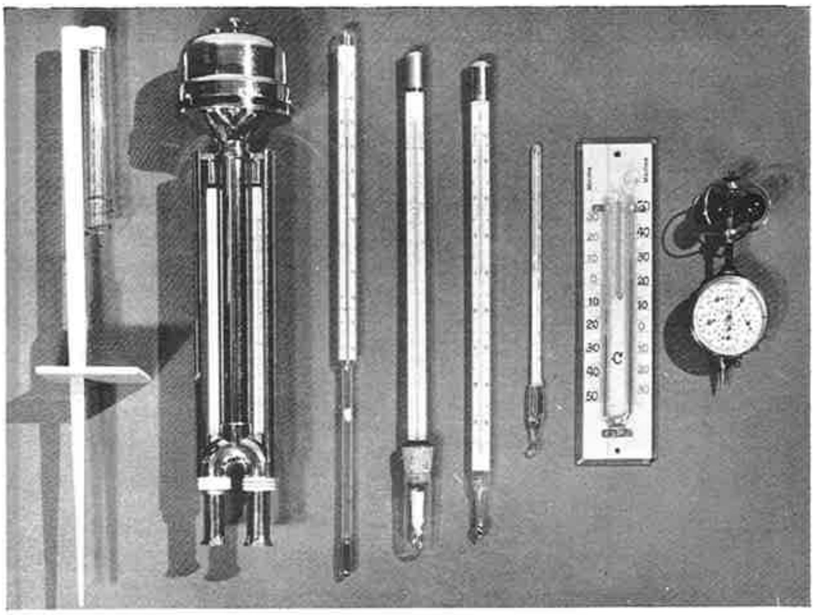

Fig. 7. Instruments used in the investigations; from the left to the right respectively: evaporation gauge, Assmann-psychrometer, soil-thermometer, wet and dry bulb-thermometers (used in the meteorological screens), Six-thermometer, another Six-thermometer (used in the meteorological screens), and portable cup-anemometer.

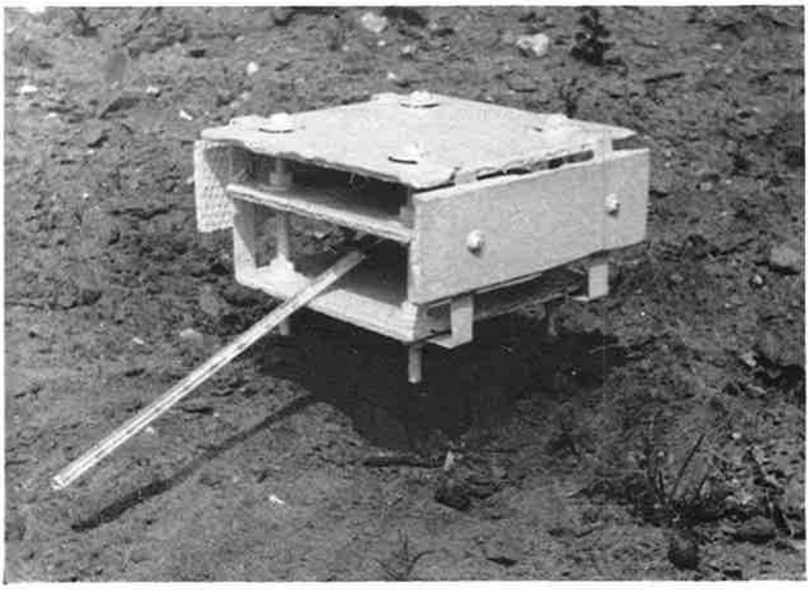

Fig. 8. A Six-thermometer in its screen.

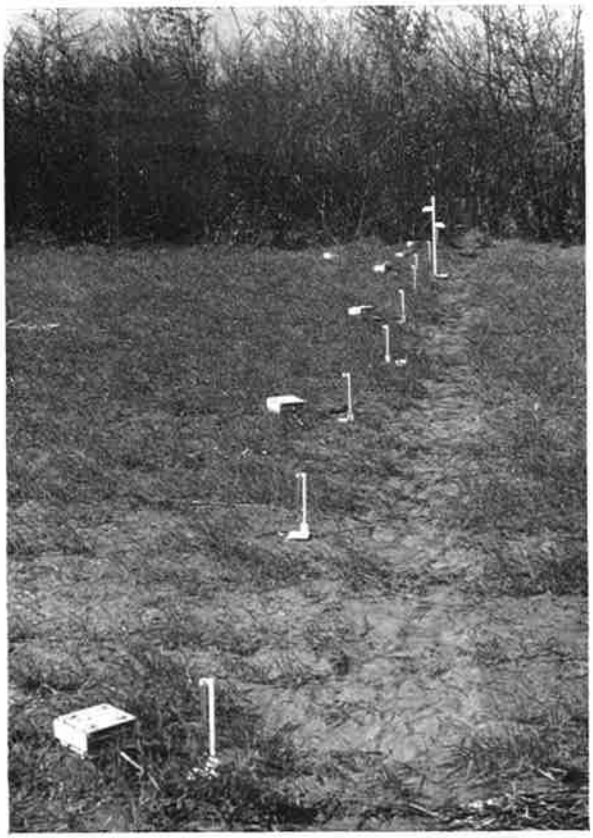

Fig. 17. Arrangement of instruments in the sheltered area in May 1944, seen from the north-east.

the minima were greater than in the following night. We have too few data at our disposal to be able to decide what should be the cause. The fog during the second night is likely to have played a part in this respect.

The distribution of the minima of the windy night of 9—10 September differs from the situation found in the previous nights. The differences between posts 3 as far as 9 included were small, which might indeed be expected seeing the rather strong wind. Post 10, on the other hand, had a considerably lower temperature minimum. As, during the night, the wind was easterly this post must have been situated in the lee of the stand, as a result of which locally outgoing radiation may have had an effect that showed itself more distinctly than that at the other posts.

When we now compare the two areas, our attention is drawn by the fact that generally speaking with ascendant sun the sheltered area was warmer than the open field (8.8^{37}; $8,10^{50}$; 9.6^{30}; 9.9^{30}; 9.11^{15}; 9.12^{50} and 10.8^{44}). With descendant sun it was just the reverse (7.18^{25}; 8.14^{03} as far as 18^{45} and 9.18^{00}) as was especially shown in the area belonging to posts 6 and 7. These data remind us of the results obtained by Bodroff (1936). In the survey of literature has already been stated what is likely to be the cause of this phenomenon, so that here we may just as well refer to the latter (see page 35). The fact that under a clouded sky the differences between the two areas were smaller (8.10^{50} and 8.12^{15}) is likewise in accordance with the information given by Bodroff.

However, a higher maximum temperature and a lower minimum temperature in the sheltered area are among the consequences of Bodroff's principle. It is true a higher maximum temperature was found along the sun-side of the stand and at posts 4 or 5 (see fig. 11), but not at posts 6 and 7. A lower minimum temperature was only found at post 7. Therefore it is clear that the relation of the temperature values in the two areas is only *partly* in accordance with Bodroff's views. That the course of temperature at posts 3, 9 and 10 cannot be explained in this way is easily understood, as these posts are directly influenced by the stands, and as Bodroff's principle is only applicable to stagnating air which is not influenced by the stand in a second way. Here we shall not enter further into the low diurnal maximum at posts 6 and 7 (an interpretation of which is given on page 128). The unexpected high (according to Bodroff)

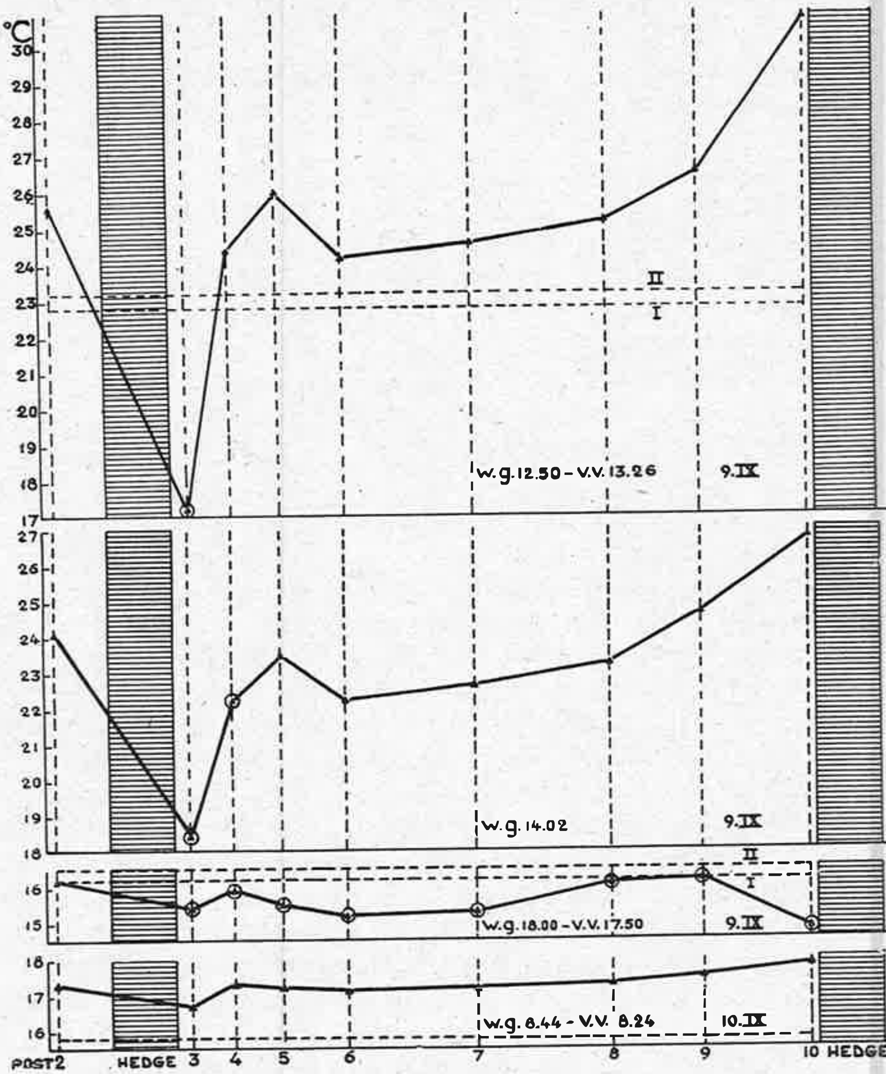

Fig. 10c. Temperature at 2 cm during the period of September 1943 (continuation).

nocturnal minima have of course been explained partly by the obstruction the stands form with respect to outgoing radiation.

Finally we have to return to the high diurnal temperature at post 5 in the sheltered area. One might suppose that this high value is only due to some fortuity in the arrangement. That this is not very probable, however, appears from the results obtained by BATES

(1911). In conformable places in the American sheltered areas he found a maximum in the yield of the crops. He thought he was allowed to conclude from this fact that locally the temperature was higher. No doubt this conclusion in itself was premature. Now that we, however, have found a higher temperature in a similar place in the sheltered area we thought there was no necessity to suppose a fortuity first of all. The cause of this high temperature, however, has not become clear to us. It is true the temperature of the radiating surface (the soil) is somewhat raised by the screening influence of the stand, but this increase in temperature is so small (about 0,5° C, as a rough calculation showed) that it cannot possibly explain the considerably higher air temperature.

Neither does the lee behind the stand provide an explanation, as the temperature of stagnating air measured at this height in the case of a negative balance of heat should be lower than that of less

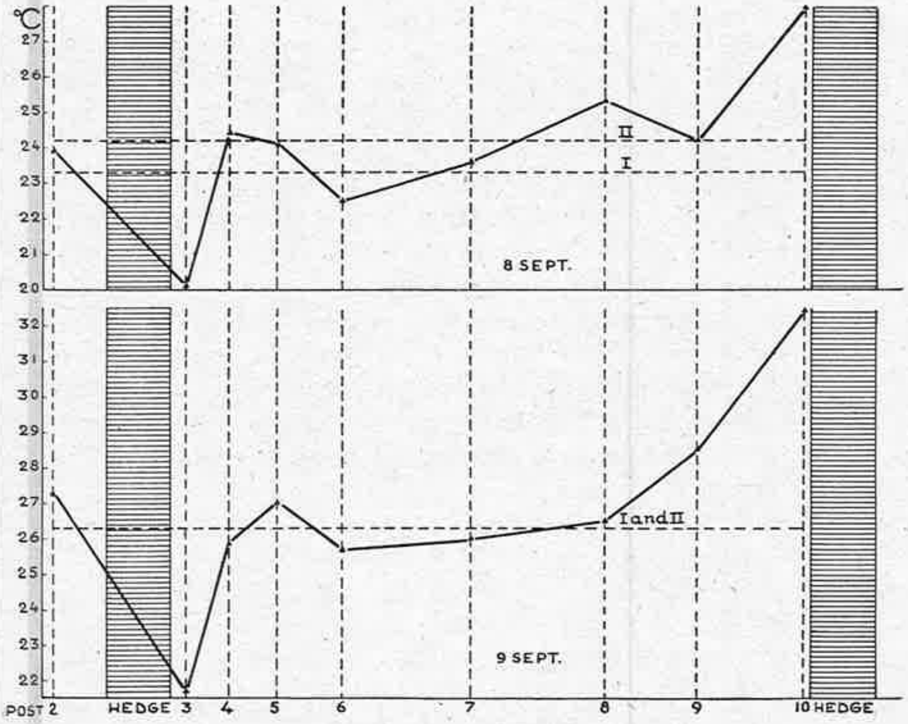

Fig. 11. Maximum-temperature at 2 cm during the period of September 1943. (Explanation see fig. 10a.)

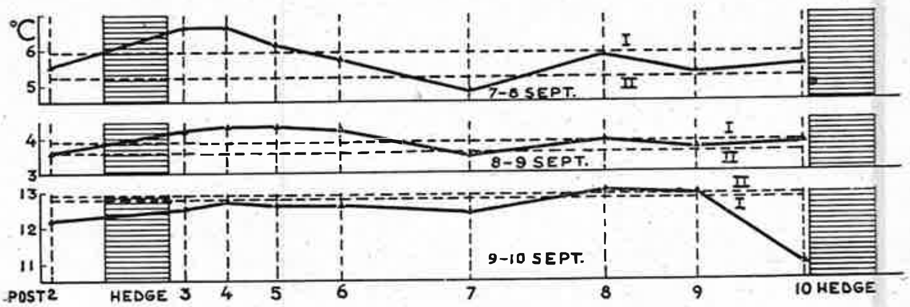

Fig. 12. Minimum-temperature at 2 cm during the period of September 1943. (Explanation see fig. 10a.)

stagnant air in the surroundings. In this way a higher temperature could only be brought about in the case of a positive balance of heat, which is in contradiction with the facts.

b. Evaporation (See fig. 13)

Generally speaking we may say that also with respect to evaporation the range of the values was greater in the sheltered area than in the open. (The relatively great range in the open in the night of 7—8 September must be due to some instrumental error.)

Further, evaporation was always greater in the daytime than at night. The cause of this phenomenon is plain, as during the night the temperature was lower, the degree of air humidity was higher and the wind lighter than in the daytime.

As a rule evaporation was greater in the open than in the sheltered area. Therefore correlation to wind velocity is plain.

When studying the distribution of the values in the sheltered area itself, we are struck by the fact that it runs, in a measure, parallel to that of the temperature. Also here a causal relation is obvious.

3. Period of 17—19 November 1943

A. Arrangements

During this period the fields were covered with low turnips. The woodlots were already leafless for the greater part. Only the oaks still had some withered leaves, as is usually the case in winter.

Just as in the case of the observations of September 1943 a cross-section between two stands was studied (see fig. 6). During these investigations post 1 was situated on the border of the south-western stand, post 9 on the border of the north-eastern one.

Two posts had been set up in the open, namely one in the middle (post I), and one on the border of the field (post II).

The thermometers had been placed at 2 cm above the ground. No evaporation measurements were made, in view of the danger of injure to the glass gauges by frost.

B. Local Weather Survey

On *November 17* the weather was grey (Sc) and rainy throughout the day; there was little wind.

During the *night of 17—18 November* the sky was temporarily clear and for the rest covered with Sc. There was a very light wind (0) and a heavy dew was falling.

In the morning of *November 18* it was hazy and rather clouded (9^{00}; Sc + fn; $^{8}/_{10}$). Later on (10^{52}) cloudiness decreased, owing to which from time to time the weather was sunny. The sky did not become quite clear (12^{57}; Sc + Cu; $^{3}/_{10}$), and sometimes the sun disappeared for a longer period (13^{34}—13^{57}). Throughout the day the wind was light (1 or 1—2) from eastern directions.

During the *night of November 18—19* soft rime occurred.

During the forenoon of *November 19* there was an eastern wind, being somewhat stronger (3) than on the previous day. Cloudiness (Sc) made the sun invisible and it was foggy.

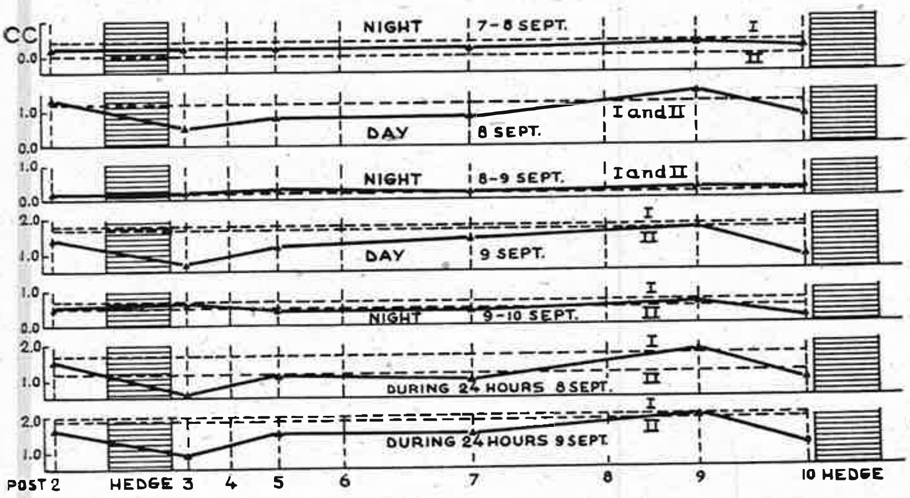

Fig. 13. Evaporation during the period of September 1943. (Explanation see fig. 10a.)

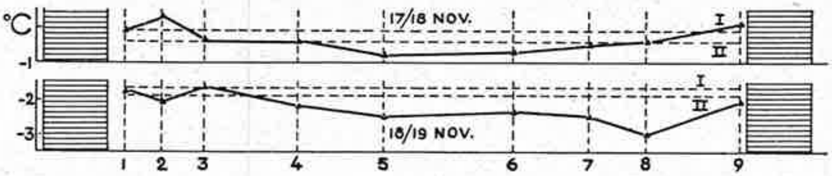

Fig. 16. Minimum-temperature during the period of November 1943.

Also in November a shaded strip, and an extra heated one on the sun-side of the stand were perceivable (18.13^{34}; 18.14^{25} and 18. maximum). In most cases only a slight indication was found of the maximum beside the shade zone. At post 5 a relatively high temperature was found, however, at 14^{25} on November 18 and this post was at the moment the first outside the area shaded by the stand. This fact indicates that here again we are concerned with the temperature maximum found in September, but owing to the low sun's altitude, the shadow is wider now and the maximum is lying at a greater distance from the stand. Also in this case we cannot give an explanation of the phenomenon, but the facts seem to indicate that the high temperature zone is a typical feature of strips of ground where light and shade meet.

Except for the diurnal maxima (see fig. 15), it appears that the situations found are almost completely in accordance with the regularity found by BODROFF. The great difference between the sheltered area and the open found at $12^{56}/13^{34}$ on November 18 makes us suppose, however, that in the time between the two observations an irregularity in the weather conditions has occurred, which may have increased the differences in temperature between the two regions. Therefore these observations do not form felicitous examples to illustrate BODROFF's "microclimatic law".

A regular distribution of the minimum temperature (fig. 16) was found in the sheltered area during the almost windless night of 17—18 November. In this case the temperature in the sheltered area was generally lower than that in the open. There was a great similarity to the distribution found in September 1943, when in the area half-way two screens the lowest temperatures occurred.

That night in November temperature fell to a little below zero both in the open and in the sheltered area. In the sheltered area night-frost was strongest. Also in the night of 18—19 November the minimum temperature in the sheltered area was lower than that in the open. The distribution of values was not so regular as in the previous night. There was now more wind than in the night before and the difference between the two areas was somewhat larger.

In opposition to the observations made in September 1943 the nocturnal minima during these November-observations were in accord with the results obtained by BODROFF. Apparently during the nights in September some circumstances have occurred which counteracted the effect of outgoing radiation to a higher degree in the sheltered area than in the open. It is obvious we should in this connection think of formation of mist or fog. For in this case heat is released and also the mist itself reduces outgoing radiation in a measure. That mist occurred during the September nights may appear from the weather survey. As, generally speaking, air humidity is greater in the sheltered area than in the open (see the data on air humidity during other periods of observation) the mist may have been denser in the sheltered area than in the open.

Finally, with respect to the nocturnal minima (fig. 16), the relatively low temperatures which were sometimes found close to the stands were remarkable. Concerning the observations made in September it has appeared that at least in one case this feature of the temperature distribution is likely to have been brought about under the influence of wind. A similar argumentation, however, cannot be applied to the almost windless night of 17—18 November. As we have already demonstrated the distribution of temperature found in this night must have arisen under the influence of outgoing radiation. Also the low temperature near the south-western stand may be effected by outgoing radiation, for it seems obvious that we are here concerned with an equivalent of the nocturnal forest wind (KOCH 1934). Of course a strong current of air is not to be expected in the case of the narrow stands in the region studied. Therefore we may conclude that the phenomenon may be observed most distinctly when there is little or no wind. This may also be the reason why the phenomenon did not occur near the north-eastern stand.

The same phenomenon was observed in the night of 18—19 November, and now also near the stand to the north-east of the experiment area. Now, however, the low temperature had shifted a little towards the middle of the field. We are not able to give an explanation of this effect, as we have not enough data at our disposal.

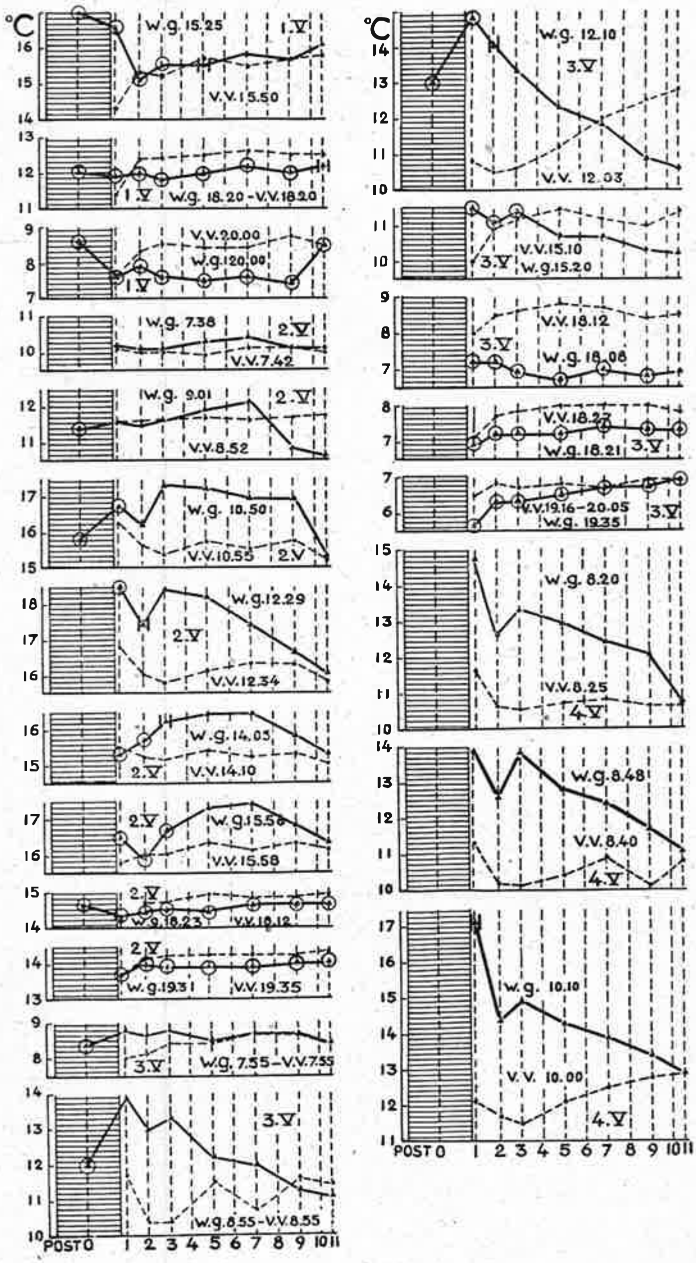

Fig. 19. Temperature at 10 cm during the period of May 1944.
(Explanation see fig. 10a.)

The diurnal average of the relative air humidity amounted to about 72 cent on May 2, and gradually decreased, till on May 4 it was about 54 per cent.

During the greater part of the period the temperature was somewhat below normal.

From the data on the wind direction it appears that on May 2 the wind was almost perpendicular to the screens. On May 1 and 3, however, the angle formed by the direction of the wind and the longitudinal axis of the screens was considerably smaller.

C. *The Data*

a. *Temperature at a Height of 10 cm* (See figs. 19, 20 and 21)

When considering these data we are in the first place struck by the fact that in the open the differences between the values of the temperature were greater than in the cases treated of so far. It is obvious that the half-grown rye on either side of the field, and the convex cross-section of the field are responsible for it, together with the strong wind. In this connection the fact that the number of observation posts in the open was now much greater than in the previous observation periods can only have been of minor importance. The half-grown rye, and of course the full-grown crop later on, cause "woodstand"-effects in the open itself. The phenomenon was to be observed especially in the middle of the day (2.12^{29}—12^{34}; 3.12^{03}—12^{10}; 4.10^{00}—10^{10}).

Notwithstanding the relatively great differences in the open the differences in temperature that simultaneously occurred in the sheltered area proved in most cases to be somewhat greater.

Also now most data are in accord with BODROFF's results. As the only exceptions the minimum temperatures during the night of 2—3 May (fig. 21), and the maximum temperatures of May 3 (fig. 20) ought to be mentioned.

When examining the data more closely, however, we see that on May 2, at about 4 p.m. (2.15^{56}—15^{58}) the field in the sheltered area had a distinctly higher temperature than the field in the open. Therefore it is clear that on this day the change (after which the open had a higher temperature than the sheltered area) took place rather late in the day in comparison with the results treated of in the previous pages. We will consider this phenomenon more closely.

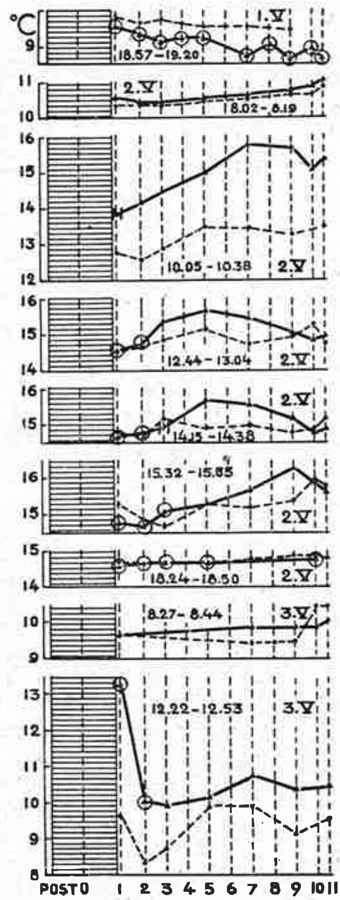

Fig. 22. Temperature at 25 cm during the period of May 1944.

in general may have been liable to fluctuations. From the observations made at about 10^{30}, 12^{03} and 15^{03} in the open it appears that this does not seem to be the cause of the difference; at these times the temperatures were fairly constant. It seems more likely that the different manner in which the temperature was measured has played a part, as it has appeared that the readings from the dry bulb thermometer of an ASSMANN-psychrometer are not always comparable with other thermometer readings.

c. Absolute and Relative Humidity (See figs. 23 and 24)

On the evening of May 1 air humidity was almost the same in the two areas. This was shown both by the vapour pressure and the relative humidity. In the morning of May 2 the differences were also slight.

At about 10 a.m. on this day, however, distinct differences were observed (2.10^{05}—10^{38}). At this time the vapour pressure was considerably higher in the sheltered area than in the open, the relative humidity, on the other hand, was highest in the open. This was caused by the high temperature in the sheltered area (see temp. at 25 cm). The observations of 12^{43}—13^{06} and 14^{17}—14^{38} showed much smaller differences. They show, however, the same tendency. Also in these cases the temperature was higher in the sheltered area than in the open.

Distinct differences were also observed in the forenoon of May 3. Both from the data concerning the vapour pressure and from those regarding the relative humidity it appears that, in contrast with the day before, the air in the sheltered area was considerably drier than

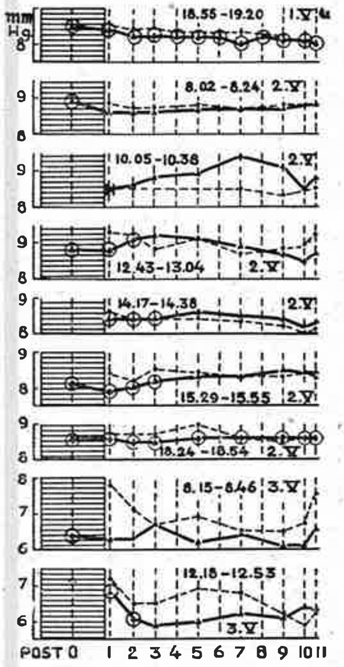

Fig. 23. Absolute humidity (vapour pressure in mm Hg) at 25 cm during the period of May 1944.

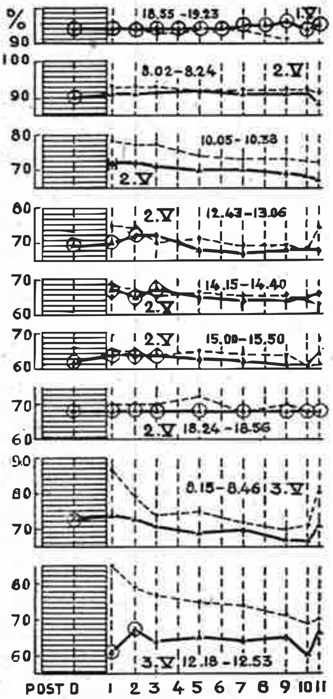

Fig. 24. Relative humidity at 25 cm during the period of May 1944.

Also during the *night of June 16—17* the air remained unstable and showers occurred.

In the early morning of *June 17* a heavy shower occurred (6^{30}) and for the rest of the forenoon cloudiness was as variable as on the previous day, with showers and thunderstorms. After about 13^{30} cloudiness decreased, so that the afternoon was sunny. Only some Cu hum were observed. The evening was bright.

The wind was on this day at first (8^{30}) rather light (NW 2). Soon it became stronger (9^{51}; 4 Beaufort) and turned to WNW. When showers were passing over the wind was temporarily stronger. In the afternoon wind force decreased a little (force 3—4 at 14^{04}) and the wind turned to NNW.

In the morning of *June 18* the weather was bright and sunny, while a light wind was blowing.

According to observations made at De Bilt the wind was SW throughout the day of June 15 and rather strong (maximum 13 m/sec). In the latter part of the night the wind force decreased considerably (max. 7 m/sec), and on June 16 it reached only moderate force (max. 9 m/sec), blowing from directions between SSE and W. During the night of June 16—17 the wind velocity was light to moderate (max. 6 m/sec) but on the 17th it increased much (max. from 13 to 14 m/sec), blowing from NW and NNW. In the night of June 17—18 only light wind occurred (max. just over 4 m/sec), while also the following morning the wind was at first rather light (max. 8 m/sec, from SSW).

Especially in the beginning of this period the temperature was below normal. Relative air humidity was liable to strong fluctuations and on 15-18 June respectively amounted to about 75, 88, 65 and 70 per cent.

The amounts of precipitation were rather considerable.

From the wind directions it must be concluded that on June 15 and 16 protection in the sheltered area must have reached about its maximum, whereas on June 17 the wind was blowing almost parallel to the screens.

The bad weather conditions made the field work very difficult during this period. As a result of the sudden showers circumstances were very uncertain, owing to which especially the temperature was liable to rapid and strong fluctuations. A number of observation series could not be taken into account, because many of the readings were made during such rapid temperature changes. Further the taking down of data was so diffcult during the violent showers with rain and wind that sometimes the observations had to be interrupted. The weather conditions and also the fact that the synchronization of observations had as yet been carried through imperfectly — at the time we had not yet a field telephone at our disposal — caused the impossibility of comparing the data obtained in the two regions in some cases.

C. *The Data*

a. *Temperature at a Height of 2 cm* (Figs. 26, 27 and 28)

In the small number of observation series concerning which the comparison of the two regions could be made only little of the

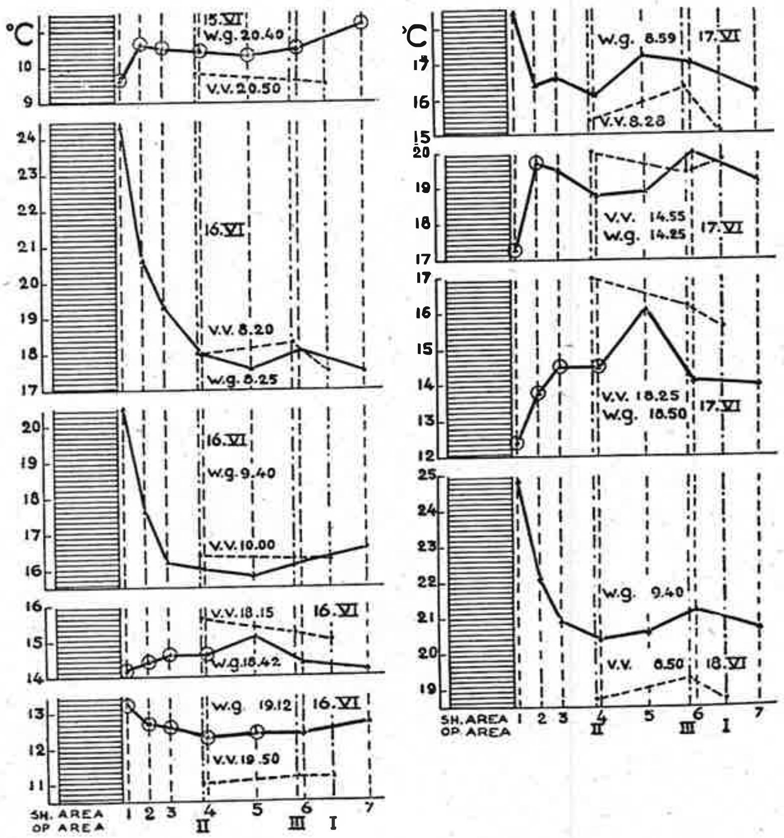

Fig. 26. Temperature at 2 cm during the period of June 1943.

results of the measurements made in the rye were not taken into account. With respect to the results obtained in other periods it ought to be remembered that during this period as well as in May 1944, as we have seen in one of the preceding sections, the measurements were made in the limited area of the shaded zone and the temperature maximum next to it.

B. Local Weather Survey

Throughout the day of *April 20* there was a rather light wind (2—3), blowing at first from WNW, later from NW, and during the greater part of the afternoon from W. In the evening (18^{42}) there was hardly any wind. The little wind which was blowing came from the west, which was indicated by a cloud of smoke.

The day was rather sunny. Some Cu and Cu hum occurred, in the afternoon accompanied by some Ci, and in the evening by some Ac.

During the *night of April 20—21* the sky was clear, night-frost occurred.

On *April 21* the wind was SE and considerably stronger than on the previous day (at 7^{40} 3 Beaufort; 9^{56} and in the afternoon 5). Also this day was sunny. In the afternoon, however, much Ci occurred.

On *April 22* the sky was at first overcast (Sc).

During this period no rain fell at Oldebroek.

According to observations made at De Bilt the wind on April 20 was light to moderate (maximum 7 m/sec), from various directions (W-N-E); during the two following days it was considerably stronger (maximum about 15 m/sec). On 21 April the wind was blowing from ESE — SE, on April 22 from SE — SW. During the first two nights there was a light wind (W and ESE), in the night of April 21—22 a strong one (SE).

The relative air humidity was small; on April 20 it amounted to an average of about 55 per cent, on April 21 to an average of about 45 per cent.

The air temperature was on April 20 a little and on April 21 and 22 considerably higher than normal.

From the local data on the wind direction we see that in the forenoon of April 20 the wind was blowing almost parallel to the stands; in the afternoon, however, the wind direction was more favourable. Also on April 21 the wind direction was almost parallel to the screens.

The wind direction observed at Oldebroek on April 20 differed considerably from that observed at De Bilt. This was to be expected on a sunny day with a light wind (Zuider Zee-effect).

C. The Data

a. Temperature at a Height of 2 cm (Figs. 30, 31 and 32)

One of the greatest disadvantages of the arrangement used is that we, after being compelled to leave out the data on the rye, have

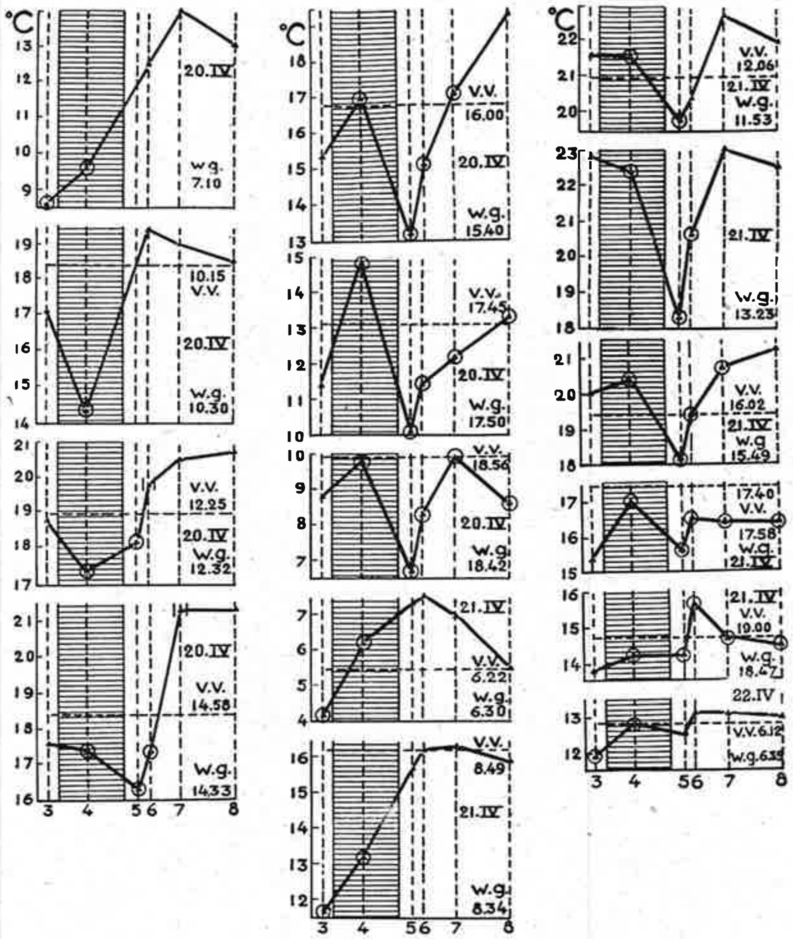

Fig. 30. Temperature at 2 cm during the period of April 1943.

Just as in May 1944 a cross-section of one field in the sheltered area was compared with one in the open. The thermometers had been placed at 10 cm above the ground.

Owing to the fact that the data on the arrangement used in this period have got lost, we had to rely upon our remembrance and therefore we cannot describe it exactly. Thus it has not been possible either to interpret the details of the data. We had to satisfy ourselves with tracing the general tendencies.

B. Synoptic Weather Survey

After a cold front had passed over in the course of the evening of Monday April 8 our country came under the influence of an air current of arctic origin. This air current was cut off during the night of April 9—10 as a result of the displacement into an easterly direction of a high, which at first had been situated west of Ireland. The centre of it now came above England.

In the meantime in a front west of Iceland a disturbance had formed, which began to move round the region of high pressure mentioned above.

This high flattened a little during April 11 and strongly developed into a western direction. Thus the winds became light. The warm front of the disturbance which had formed near Iceland reached the northern part of our country in the course of the evening of April 11, but after this its activity rapidly decreased. A following disturbance had lost its activity before it had reached our country (April 12). The distribution of pressure in our surroundings now became rather flat. A separate low appeared just east of our eastern frontier on April 13.

C. Local Weather Survey

In the early morning of *April 10* cloudiness was about $^{9}/_{10}$ (Sc). In the course of the forenoon cloudiness decreased somewhat, so that at intervals the sun became visible. Throughout the day there was a cloud deck of Sc + Cu, cloudiness $^{8}/_{10}$—$^{5}/_{10}$. In the evening (19^{00} and 19^{20}) there was also a deck of Sc + Cu, cloudiness being $^{8}/_{10}$.

On this day the wind was blowing from NW—NNW, the wind force being from 3 to 4 Beaufort up to the afternoon, and from 1 to 2 in the evening.

During the *night of April 10—11* some rain was falling.

In the morning of *April 11* the cloud deck at first consisted of

Cs + Cu, cloudiness $^{6}/_{10}$ (7^{12}). Soon, however, cloudiness increased (9^{30}; Cs + Cu; $^{10}/_{10}$; sun visible). Throughout the day cloudiness remained $^{10}/_{10}$, the deck consisting of Cs + Cu + As + Ac and in the afternoon moreover Sc was observed. During the evening the cloud deck consisted of Ac + Sc cloudiness being again $^{10}/_{10}$. From these heavy clouds now and then some drops of rain were falling.

Throughout the day the wind was almost constantly blowing from W, wind force being 2 and later in the morning from 3 to 4, 4 in the afternoon, and in the evening from 2 to 3.

During *April 12* the sky was for the greater part of the day overcast (Sc; $^{10}/_{10}$), the forenoon being rainy. Only in the evening there was less Sc (cloudiness $^{2}/_{10}$—$^{8}/_{10}$). Moreover, some Cu and Ac were visible at this time.

The wind was throughout the day from WSW to W, from 2 to 3 Beaufort.

In the morning of *April 13* there was a broken Sc-cover ($^{4}/_{10}$—$^{9}/_{10}$), the wind being WSW 1.

According to observations made at De Bilt the wind on April 10 was from N to NNW and rather strong (maximum 15 m per second). During the first six hours of April 11 light wind occurred, blowing from the west (maximum 4 m/sec), while during the rest of the day the wind was moderate, from W to WSW (maximum about 12,5 m/sec). During the night of April 11—12 the decrease in wind velocity was only slight (maximum velocity 9 m/sec), the wind being W. On the day of April 12 the maximum velocity was 10 m/sec, the direction being from W to WNW. During the night of April 12—13 the maximum wind velocity was only 2 m/sec, the direction being W; in the early morning of April 13 the maximum was about 3,5 m/sec, direction SW.

Throughout this period the temperature was below normal, the lowest temperature being observed on April 10.

The relative air humidity was liable to strong fluctuations. On April 10 it amounted to an average of upwards of 50, on April 11 about 60, on April 12 nearly 80, and on 13 April about 73 per cent.

D. *The Data*

a. *Temperature at a Height of 10 cm* (Figs. 34 and 35)

Up to and included the observation made at 16^{05} the temperature on April 10 was on the whole higher in the sheltered area than in the it seems probable that also in this case this unexpected effect should be ascribed to rainfall.

During the rest of the day no distinct differences were observed between the sheltered area and the open. It is clear that this must have been caused by the fact that there was only little incoming radiation as a result of the thick cloud deck.

Also in the morning of April 13 the sheltered area was at 9^{00} colder than the open, which was probably again caused by rainfall.

The nocturnal minima should also be amply discussed (see fig. 35). During the first night (April 9—10) and during the last (April 12—13) the differences between the two areas were smaller than in

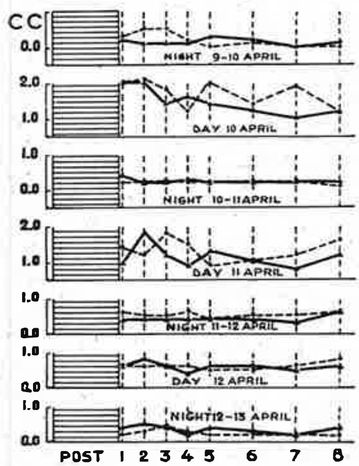

Fig. 36. Evaporation during the period of April 1946.

the nights of April 10—11 and 11—12. During the last three nights the wind was W, and considerable differences in velocity occurred. The latter was lowest (maximum 2 m/sec) during the last night. As from the data obtained during other periods of investigation it appears from these nocturnal minima that in very low velocities the differences between the sheltered area and the open become smaller.

Also during the first night the differences between the two regions were small. Then the wind was, however, NNW, blowing almost parallel to the screens. Yet, also in this case the sheltered area was somewhat colder than the open, from which we may conclude that also under these circumstances the wind velocity in the investigated part of the sheltered area was even smaller than in the open. The same must be concluded from the daytime situation on April 10, when the wind was also from NW to NNW.

b. Evaporation (Fig. 36)

During this period evaporation was small, as a result of the weather conditions.

Also now the value of evaporation was higher in the daytime than at night, higher on days with moderate wind than on those with little wind.

On days with moderate wind the value of evaporation was distinctly higher in the open than in the sheltered area.

8. Period of 3—17 May 1946

A. Arrangements

In the chapter dealing with method and technics it has already been stated that the arrangement used during this period (see fig. 6) was not satisfactory, no more than in April 1943. The posts were situated partly in the full-grown rye, partly in the young oats, thermometers being placed at 10 cm.

When compared with the results obtained in other periods the data obtained in the rye-field were all but incomprehensible, and it is obvious that this was caused by the microclimatic properties of the crop itself, and by the path we were compelled to make through it. Because of this we shall leave the data obtained from the rye-fields for the greater part out of consideration. For the following reason the data concerning the nocturnal minimum may be valuable, however. The cold air which has been cooled down in the toplayer of the crop and reaches the thermometers by sinking down into the path will give a reliable picture of the distribution of temperature in the surroundings at a height equal to that of the crop, the more so as its temperature will only be subject to small changes in the path.

Of course the low oats can have caused only little disturbance to the thermometers placed at 10 cm. Therefore our considerations will have to be based chiefly on the measurements made in the oat-fields.

In this connection we should remember the fact that also in the open the field of oats was bordered by fields of rye, so that, if the wind was favourable, the station open area must also have been more or less sheltered. Yet, we may assume that shelter was more important in the sheltered area than in the open.

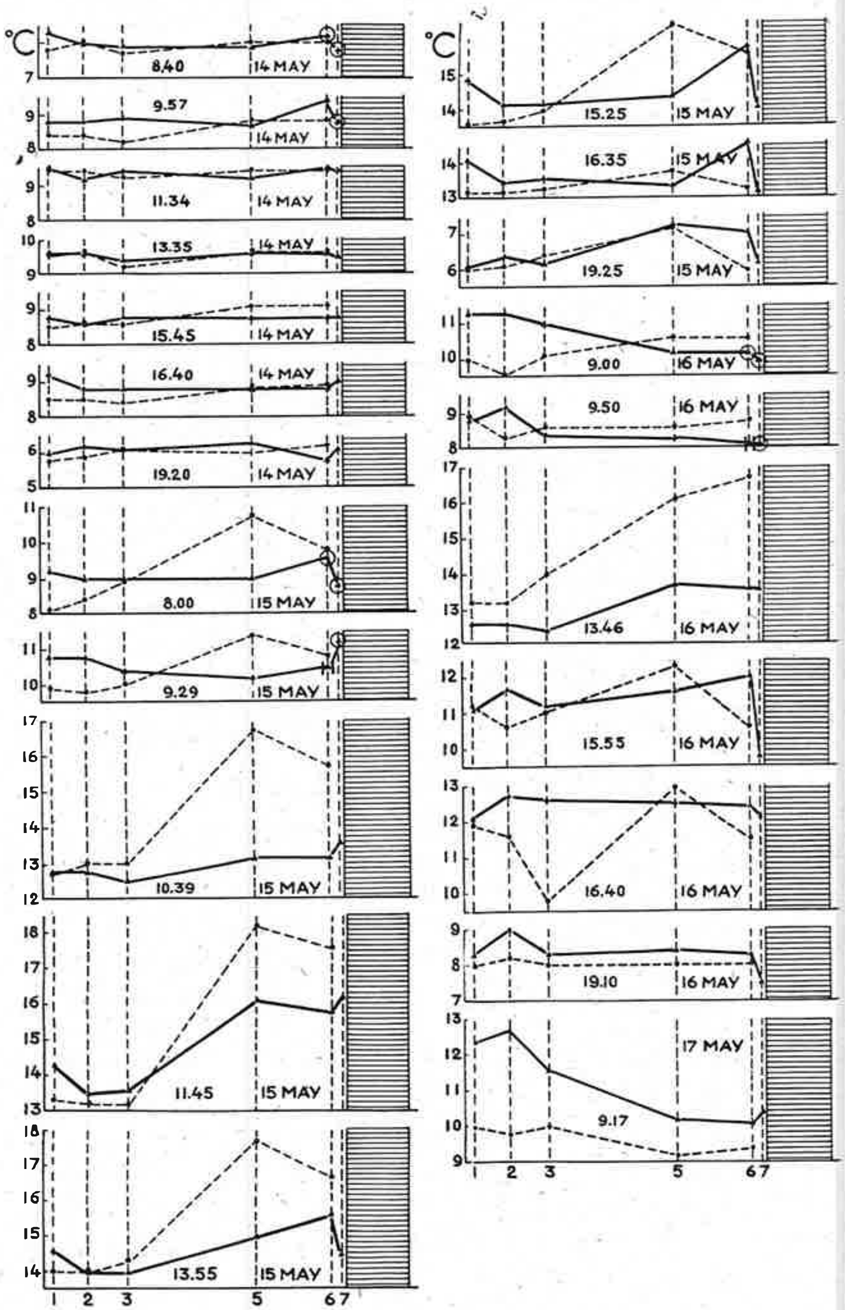

Fig. 37. Temperature at 10 cm during the period of May 1946.

in the sheltered area and in the open were all but equal throughout the day. The differences between the posts in the sheltered area were also very small. Only late in the afternoon (16^{40}) the temperature was somewhat higher in the sheltered area than in the open. These facts are easily understood as almost throughout the day the sky was thickly overcast (compare the results of the former periods of investigation). The circumstance that throughout the day the wind was blowing almost parallel to the screens may also have contributed to this effect. Not before late in the afternoon the sun temporarily became visible, and apparently it could then heat the lowermost air layers in the sheltered area more than those in the open. As similar observations were made in the following days, we shall not

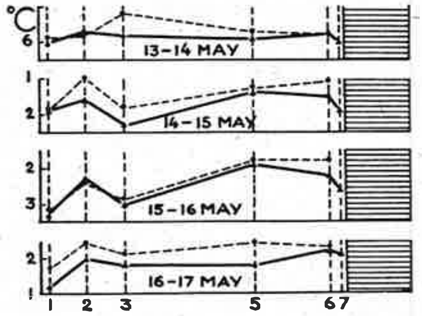

Fig. 38. Minimum-temperature at 10 cm during the period of May 1946.

try to give an explanation of this phenomenon here, but in the following pages.

On the following days, when it was alternately sunny weather, the differences were greater, also between the posts in the sheltered area. Our attention is attracted by the fact that, apart from some exceptions (15.10^{39}; 15.13^{55}; 16.13^{46}), the temperature in the field of oats lying in the sheltered area was always higher than in the open. This situation was continued till late in the evening (14.19^{20}; 15.19^{25}; 16.19^{10}). The nocturnal minima, however, were as a rule lower in the sheltered area than in the open (fig. 38). Therefore it is clear that the point of time at which the reversal took place must on these three days have appeared very late.

We shall now occupy ourselves first with one of the exceptions mentioned above, viz. with the one of 16.13^{46}. The situation found at this time is easily explained in the following way. The fairly

Finally we have to draw the attention to the low temperature on the edges of the oat-fields both in the sheltered area and in the open. This low temperature may also be caused by a current of cold air. In this case the latter would originate from the plane formed by the tops of the rye plants, and would also be an equivalent of the nocturnal forest wind.

9. Period of 2—6 September 1946

A. Arrangements

During this period the stands were still in full leaf. Most fields had a low cover of turnips. The ground above which the measurements were made, however, was almost bare.

The temporary microclimatological station in the sheltered area comprised a cross-section of a good 36 m between two stands. In the open the instruments were placed in a row of 17 m across the field (see fig. 39 on plate VI). At all observation posts evaporation gauges had been placed, and moreover soil thermometers at posts 1, 4, 9 and 12 of the sheltered area and posts I and V in the open. These thermometers were placed at a depth 10 cm below the surface.

In contrast with other periods, no temperature observations were made at the posts mentioned above. This time the thermometers were placed vertically above each other, at heights of 10, 25, 50 and 150 cm above the ground (see fig. 40 on plate VII). In the sheltered area these thermometer stands were situated at the points A and B (see fig. 6). In the open two more were placed. For want of thermometers, however, one of the thermometer stands (C) in the open was not complete. In this place observations could only be made at heights of 25 and 150 cm.

We chose this arrangement because we thought it useful to know something about the stratification of the lowermost air layers above the two areas.

During this period three meteorological screens were used together with the arrangement described above. Two of the screens were placed in the sheltered area e.g. at the same distances from the coppice stands as the thermometer stands A and B. The one in the open was situated on the edge of the field under observation (see fig. 39 on plate VI).

B. Synoptic Weather Survey

The weather during this period was characterized by strong cyclonic activity. The polar air behind the cold front that passed over our country on September 1 was very unstable, so that on September 2 heavy showers were observed. On this day our country lay in a trough of a low above southern Norway. Soon, however, it filled, so that then a flat high formed above Central Europe (September 3). In the meantime a low was approaching across the Ocean, which deepened strongly above the Azores. The occlusion front belonging to this low lost its importance above England. This was also the case with the warm front accompanying the low. During the night of September 3—4 the cold front passed over with some, for the greater part light, showers. On the following days (September 4, 5 and 6) the weather in our country kept being influenced by this low, which gradually filled up while the number of showers decreased.

C. Local Weather Survey

During the greater part of the afternoon of *September 2* the sky was heavily overcast (Sc + Ac + As + Cs), and heavy rain showers occurred. The wind was light (2), from SSE. Also in the evening there were many clouds (20^{00}; $^9/_{10}$; Cb + Sc), while now and then lightnings were observed. There was a light west wind (2).

During the greater part of the *night of September 2—3* the sky was clear; wind light (2), from the SW.

Early in the morning of *September 3* the sun was shining (7^{37}; near the horizon Cu + Ac + Ci). During the morning the sky cover became more and more cumuliform, and cloudiness increased (to $^6/_{10}$—$^7/_{10}$), even more during the afternoon (14^{50}; Sc + Ac + Cu; $^9/_{10}$ and 16^{36}; Cs in S; As + Sc in N; Ac + some Cu; $^9/_{10}$).

Till about 2 p.m. a gentle wind (3) was blowing from SSW. Some time later the wind backed to S (14^{50}; 2 Beaufort), and afterwards to SSE (16^{36}; 3 Beaufort).

Also in the evening almost the whole sky was covered (20^{05}; Ac + As; $> {}^9/_{10}$), and from time to time some rain was falling. During the evening the light southern wind decreased (from 2 to 1).

During the greater part of the *night of September 3—4* the sky was heavily overcast (Ac). Early in the morning cloudiness decreased (6^{30}; Ac + Cu; $^7/_{10}$) and the sun began to shine. There were only some Ac + fc, while a light wind was blowing.

In the morning of *September 4* cloudiness increased (9^{35}; Ci + Cs + Cu + Ac; $^7/_{10}$ and 10^{03}; $^9/_{10}$). During the greater part of this morning the wind was SSE 4. About noon the sun was shining

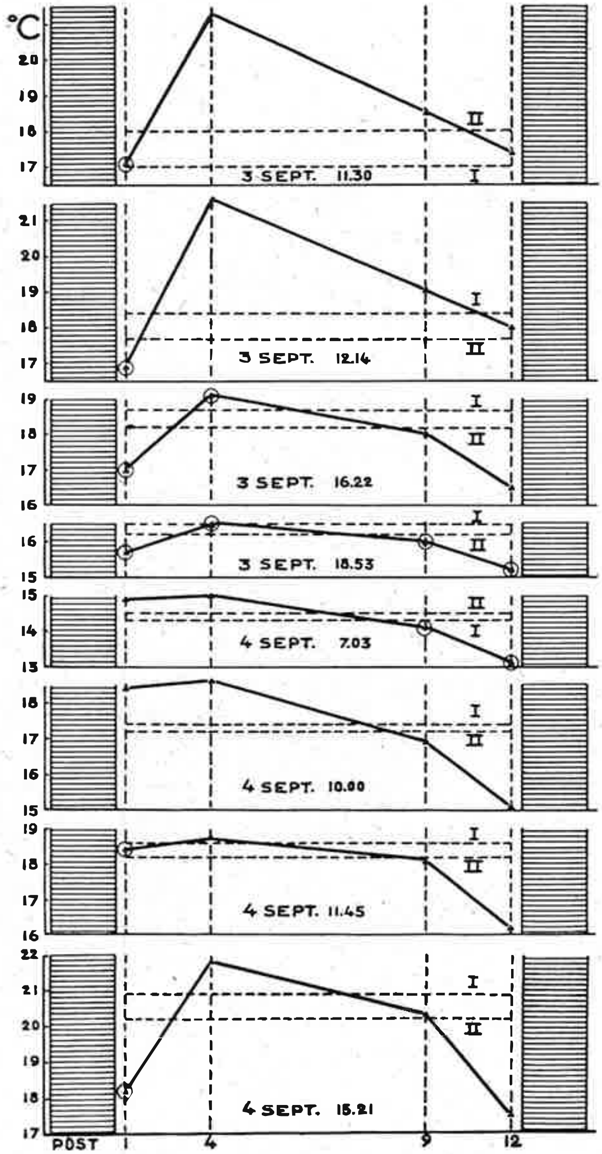

Fig. 41a. Soil temperature at 10 cm during the period of September 1946.

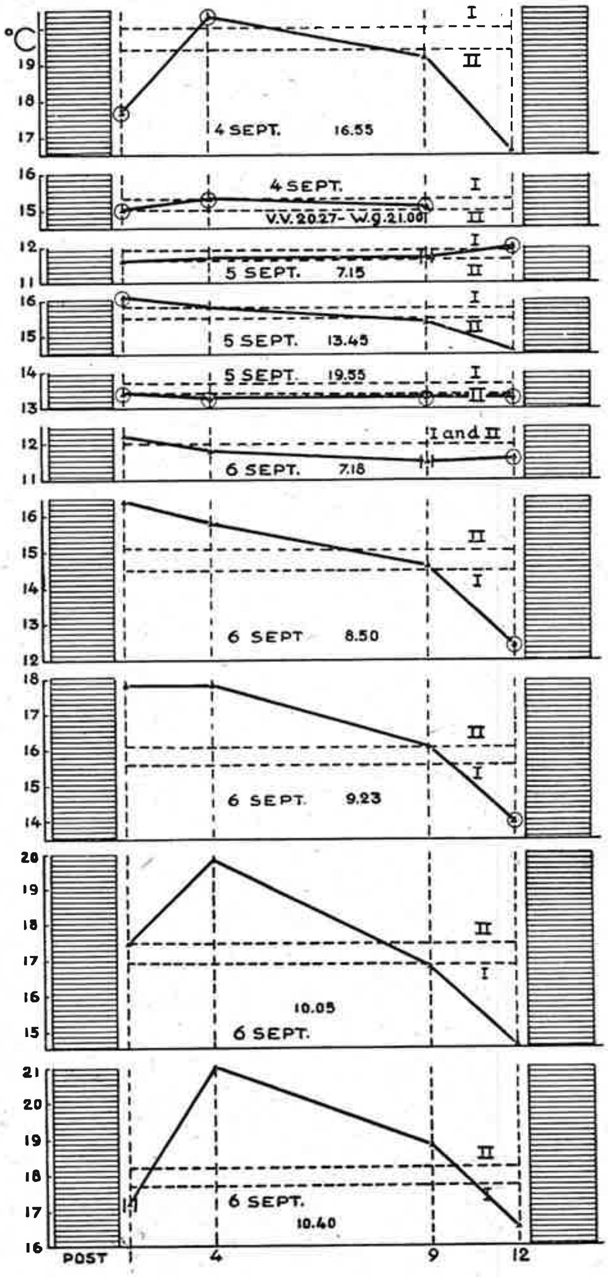

Fig. 41b. Soil temperature at 10 cm during the period of September 1946 (continuation).

compared with one another, and therefore it is no use mentioning all data obtained in these series of observation. Therefore we have plotted with respect to time the data obtained at two posts (4 and 9) of which owing to their situations with regard to the hedges it might be expected that the temperature had not been liable to the most strong fluctuations.

In this way it has appeared that, generally speaking, the differences between relative humidity in the open and in the sheltered area were slight. Yet, in most cases the air above the open was somewhat drier than that above the sheltered area.

The greatest differences between the two areas were found in the morning of September 3. At this time there was likewise a distinct difference between posts A and B in the sheltered area, the relative

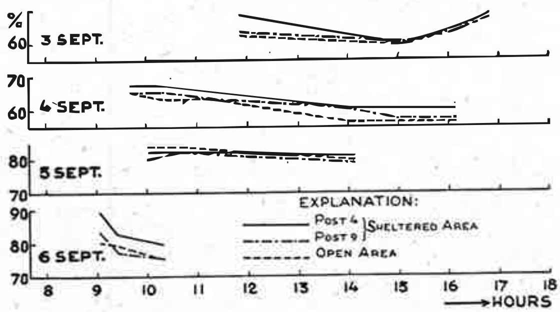

Fig. 45. Course of the relative humidity at 25 cm during the period of September 1946.

humidity being higher at post A than at post B. This must have been caused by the more definite lee at post A. The difference in shelter also explains the difference between open and sheltered area.

e. Evaporation (Fig. 46)

With respect to evaporation we need not say much, as the results are clear. Also during this period it was observed that during the night evaporation was considerably smaller than in the daytime, as was to be expected. Moreover, the differences between the two areas during the night were nil.

In the daytime the differences were clear. On September 4 they were even considerable, as a result of the strong wind on this day. Now the distribution of values in the sheltered area showed a distinct course. From the south-western stand the value gradually increased in the direction of the north-eastern one. It is to be understood that this picture must have been caused under the influence of the strong wind, blowing from SSE to S.

We dare not give an opinion on what may have caused the irregular distribution of the much stronger evaporation in the open, because fortuities due to the unevenness of the ground and deviations in the instruments may have played a part.

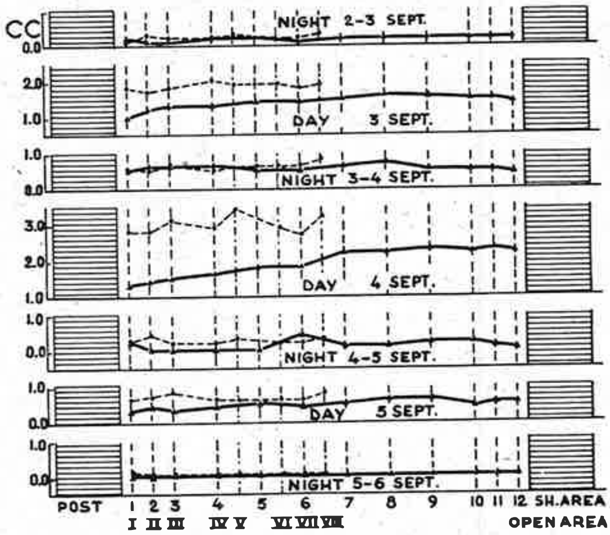

Fig. 46. Evaporation during the period of September 1946.

10. Some Wind and Air Humidity Measurements made during the Period of 1—5 July 1947

A. Arrangements and Weather Conditions

In this period the rye and the oats were full-grown, while the stands were in full leaf. The measurements were made above the crops mentioned (see fig. 47 on plate VIII).

Owing to the fact that there were high crops which strongly influence the microclimate themselves, these measurements are not directly comparable with those made in other periods when the crops were low. Therefore we thought it better to postpone the publication of the results obtained in the temperature measurements till a time at which we might avail ourselves of more data, and that is why we decided to give here concisely the results obtained from measurements of wind and air humidity only.

The measurements were made in the whole of a cross-section between two stands, the distance between which amounted to 31 m (see fig. 6); the wind was measured at 2 m above the ground, that is to say about 0,80 m above the plane formed by the ears of the crops of rye and oats, while air humidity was measured in this plane.

Generally speaking air temperature was during this period higher than normal, and gradually rose during the successive days. Hence the weather on July 3 and 4 was hot and decidedly summery. In the forenoon of July 2 a considerable amount of rain was falling at Oldebroek. During this period light or moderate wind prevailed.

During the wind measurements the wind was rather light (2 or 3), blowing from a direction between W and WNW, forming an angle of about 45° with the longitudinal axis of the stands.

As we are not going to analyse the details of the data, this short summary of the weather conditions may suffice.

B. The Data

a. Wind (Fig. 48)

The data are contained in the diagram going with this chapter. We may conclude that under the momentary weather conditions the wind above the cross-section examined never reached the velocity found in the open region. As at each post only few observations were made, we may set no value on the small fluctuations of the curve. The situation of the places that show the most extreme values, however, seems understandable. The lowest velocity, e.g. was found immediately behind the south-western stand, and the highest velocity at some distance before the north-eastern stand. If we were sure that the absolute value found was reliable, we should, on the ground of the results obtained by FLENSBORG and NØKKENTVED (1938 and 1940) and by NÄGELI (1943 and 1946), be allowed to conclude that oak coppice stands are among a rather dense type of windscreens.

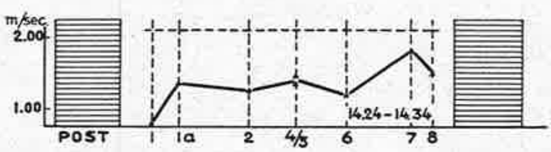

Fig. 48. Wind velocities according to one series of observations on July 4, 1947.

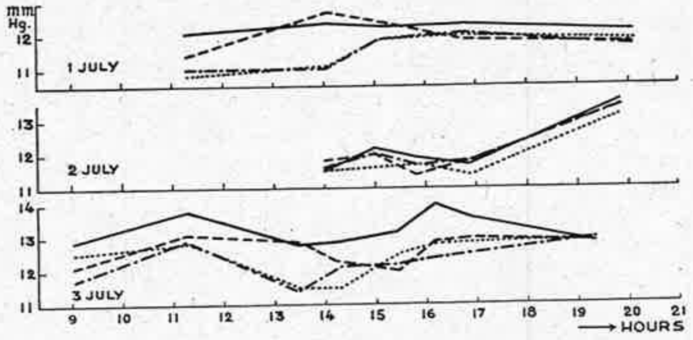

Fig. 49. Course of the absolute humidity (vapour pressure) during the period of July 1947 at the posts 2 (——) and 6 (– – –) (resp. oats and rye in the sheltered area), and at II (–··–) and VI (·····) (resp. oats and rye in the open area).

In the next chapter we shall prove that also other experiments point into the same direction.

b. Air Humidity (Figs. 49, 50, 51 and 52)

Of the data on air humidity the course of vapour pressure and relative humidity at some posts on the day of July 1, 2 and 3 have

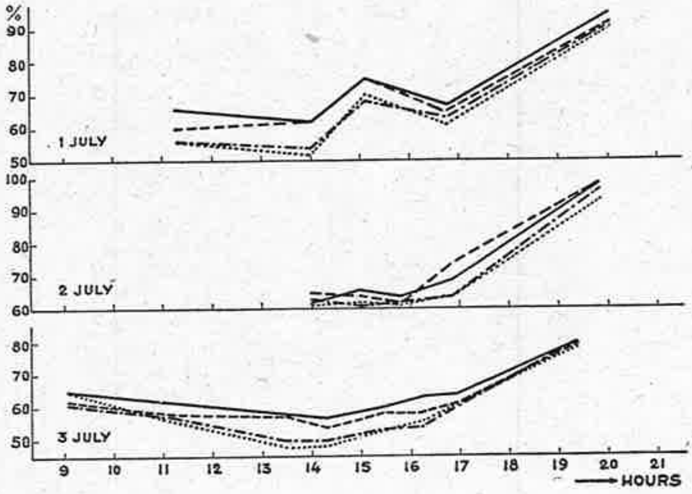

Fig. 50. Course of the relative humidity during the period of July 1947. For explanation see fig. 49.

been indicated; they have been set out with regard to time (figs. 49 and 50). Together with them we give a series of distribution curves of the two factors belonging to July 3 (figs. 51 and 52). No measurements were made in the rainy forenoon of July 2.

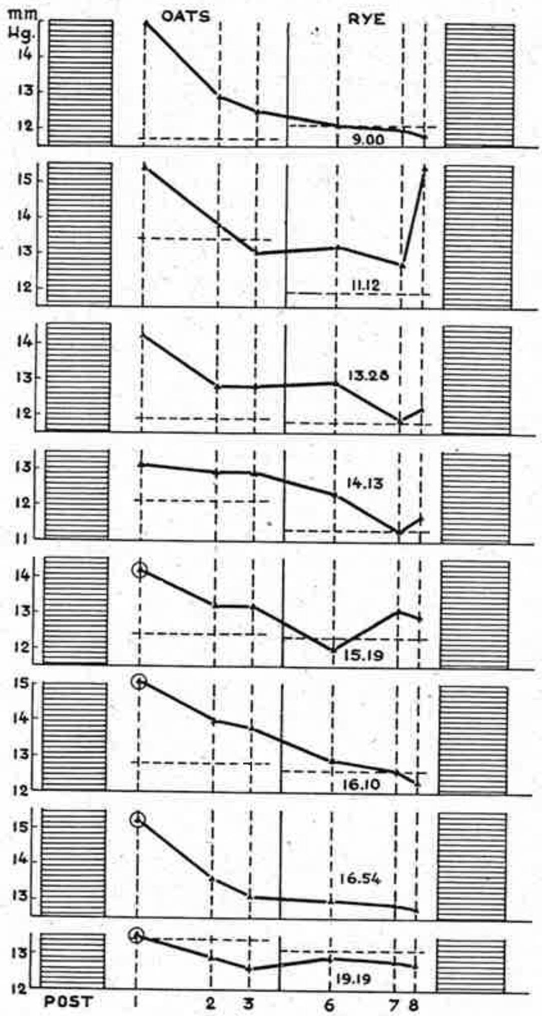

Fig. 51. Absolute humidity (vapour pressure) at several moments on July 3, 1947.

Because of reasons mentioned above it has not been possible to enter into details and we had to satisfy ourselves with the tracing

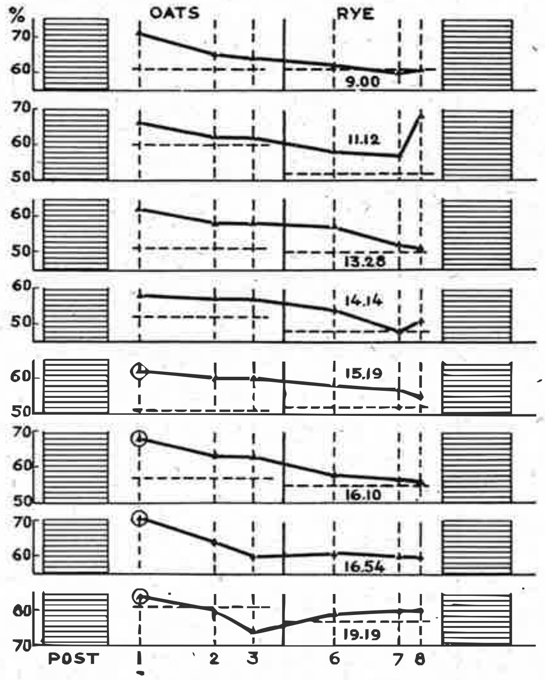

Fig. 52. Relative humidity at several moments on July 3, 1947.

of general tendencies. A look at the diagram shows that the data certainly indicate a general tendency. We may say that the air above the sheltered region was moister than that above the open. This is expressed both in the absolute and in the relative humidity.

of the area under observation. In this shaded zone the temperature in the air layer next to the ground was considerably lower than anywhere else in the area. Out of the shaded zone, into the direction of the second stand, situated in the north-east of the area the temperature above a strip of ground with a width of some meters was relatively high. We shall call this strip the "temperature maximum next to the shaded area".

Next to this temperature maximum we find an area with a width of some twenty to thirty meters, where the temperature values are noticeably lower, without great differences from place to place. This zone gradually changes into another, also with a width of some twenty to thirty m where the air temperature gradually increases into the direction of the second stand. Thus the highest temperatures are found on the sunside of the woodstands, and next to them. As of the two last named zones the former gradually changes into the latter, the limit between them, if we can speak of such at all, cannot be exactly determined. At this time of the day everywhere in the sheltered area the temperature was higher than in the open, except for the shaded zone.

Thus we must conclude that on sunny days with light or moderate wind there are four temperature zones viz. the shaded zone, the temperature maximum next to the shaded area, the zone with an equal distribution of relatively low temperatures and the zone, where the temperature is gradually increasing towards the (second) stand.

The causes for the temperature distribution described above can for the greater part easily be indicated. E.g., the area with high temperature on the sunside of the stand is undoubtedly the same as that in which HEIDEMA (1923) and SCHMOOK (1928) observed the occurrence of scald in various vegetations under the same conditions. It seems obvious that this high temperature is brought about by solar energy reflected by the stand. Moreover infra-red radiation from the branches and the leaves of the stand as a result of heating by the sun must have played a part. Seeing the results obtained by SCHUBERT (1928, GEIGER 1942), we must even assume that on sunny September days conditions are particularly favourable for the occurrence of these effects, because at this time the sun's altitude is already rather low, while, practically speaking, radiation is not yet reduced by the atmosphere as is the case during the wintermonths. Moreover, in September the stand is still in full leaf, so that most of the solar energy is caught up on the outside of the stand.

The low temperature in the shaded area does not need further explanation. The contrary is the case, however, with the temperature maximum next to the shaded area. When considering this superficially, one may be inclined to indicate the lee behind the woodstand as the cause of this maximum. On second thoughts, however, it becomes clear that this effect is certainly not to be explained by means of the theory of stagnant air. For on account of this theory an extra low temperature might be expected in this area, instead of an extra high one during the hours of the day when the balance of heat is negative.

Further it seems obvious to suppose that this high temperature might be caused by the obstruction to outgoing radiation by the stand which effect is present in the immediate surroundings both in the daytime and at night. When the temperature in this area is constant, that is to say when incoming and outgoing radiation are evenly balanced the temperature of the radiating surface (the ground) must be higher there than in other places of the region, where outgoing radiation does not meet with any obstruction. From a rough estimate, taken from a table in page 18 of GEIGER's book, however, it has appeared that in this way only a rise in temperature of the surface of the ground of at most 0,5° C could be explained. The rise in the temperature of the air above the ground will be even considerably smaller. Therefore the maximum next to the shaded area cannot be explained in this way.

Finally one might suppose that, as a result of the wind reducing influence of the stand, evaporation in this area is reduced in such a measure that after all the difference might be explained by the fact that less heat is given off for evaporation. It was found, however, that the intensity of evaporation in this area was not less than in other places.

Thus we cannot give a conclusive explanation for the existance of this area with relatively high temperature, and we should be inclined to think of some fortuity in the arrangement, if we had not found it in other periods also (see November 1943), and if not the literature contained an indication that this zone indeed is distinguished in some respect from the rest of the sheltered area. For in the American sheltered regions BATES (1911) found a larger yield of crops in corresponding places with respect to the windscreens. He thought he was allowed to conclude that there is a higher temperature in this zone. Now that we have indeed found a higher temper-

It has indeed been found in the area with the maximum temperature next to the shaded area and in the scald zone.

Thus from the things mentioned it appears that BODROFF's theory is not sufficient to explain the course of temperature in the area of the stagnant air completely. Therefore we must assume that during the hours that the sun stands highest there is at least one as yet unknown influence that counteracts the system, implicated by BODROFF's theory. We cannot say with certainty what influence this may be, but we are inclined to suppose that it will have to be looked for in the direction of a circulation system belonging to the sheltered region itself. Such a circulation system must be thought possible because of the great temperature differences that are found at a short distance from each other in the sheltered area. An upgoing current of air is to be expected on the warm sunside of the stand, a descending one, which will of course convey cooler air, on the shaded side. Of course we cannot enter into the details of this circulation system. We suppose this system interrupts the course of events at the time that, according to BODROFF's theory, the higher temperature maximum and the reversal ought to be found.

Naturally in the sheltered region the reversal takes place later in the zones with extra high temperatures than in the area of the stagnant air itself. Measurements above bare ground sometimes showed a reversal late in the afternoon, measurements above a low crop of turnips, however, a reversal in the early part of the afternoon. Therefore it is possible that, beside the place with respect to the stand, also the soil cover plays a part. That, generally speaking, this must be so is easily understood. A crop must be considered as a cover that uses radiating energy for carbon dioxyde assimilation and transpiration. Thus the bare ground will receive more heat and after the time that the balance of heat has turned it will also give off more heat to the air, owing to which the reversal is put off.

In September 1946 it appeared by means of measurements made with a series of thermometers that had been placed above each other that on the sunny mornings in this period extra high temperatures in the sheltered regions were still to be found at a height of at the least 1½ m above the ground. We think we are allowed to assume that this will also have been the case in various other periods.

During one period (April 1943) the temperature of the air just above the ground below the stand was also measured. In spite of the

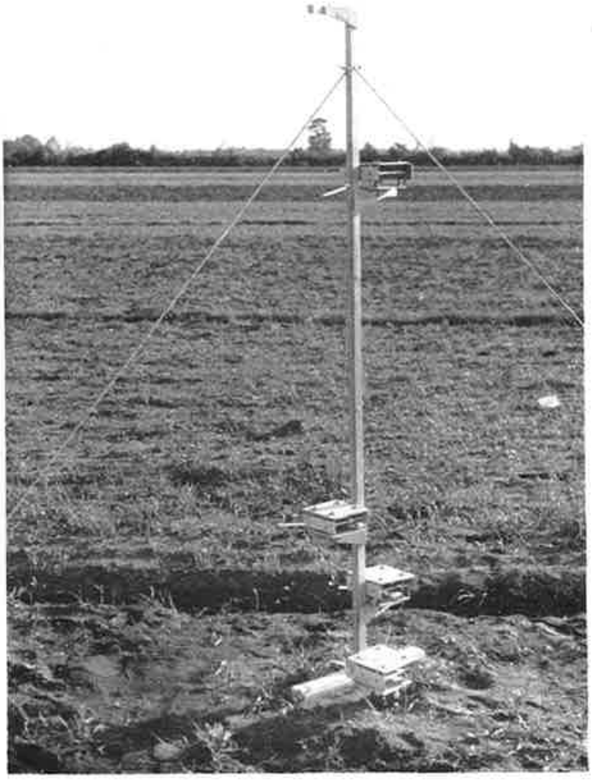

Fig. 40. Thermometer stand at post D in the open area.

Fig. 47. The sheltered area in July 1947; to the left one hedge, in the middle full grown rye, to the right full grown oats, in the back-ground farm houses. Instruments: Assmann-psychrometer (right) and writing cup-anemometer. The data obtained by means of the latter were not used.

fact that the latter was still all but leafless a distinct influence on the course of temperature was found, which was indicated by a retardation in the daily course. Moreover the temperature maximum was, in light wind, lower here than in the area of the temperature maximum next to the shade on the adjacent field. If the stand should have been in leaf, the influence would undoubtedly have been even more clear. Obviously also this temperature course must be considered to be the normal one in sunny weather and light wind. It is the "forest character" of the microclimate in the stand that presents itself in this way.

As the surface of the soil is the entry as well as the outlet for the heat in the atmosphere it would be natural to deal with soil temperature before air temperature. Owing to the small number of observations as a consequence of lack of instruments this was no use in the present case. Only during the period of September 1946 a soil thermometer could be placed at some posts in the area under observation. Making temperature measurements of the surface was quite impossible.

From the data obtained from the soil thermometers placed at a depth of 10 cm it has appeared that on sunny mornings a higher air temperature in the sheltered area coincided with a higher soil temperature, which was quite as we had expected.

B. Temperature during Sunny Parts of the Day and on Days with a Variable Cloud Deck and Light to Moderate Wind

Also the differences in temperature between an open region and a sheltered one that exist during shorter periods with sunshine on days on which the sky is overcast for the rest of the time may be explained for the greater part by the theory of stagnant air. As the properties of stagnant air have been amply discussed in the previous pages, this section may be a short one.

In periods during which the weather is characterized by unstable air numerous showers (Cb) will form in the course of the forenoon, soon covering the whole sky. In such a type of weather the sun will be shining for some hours before the showers develop. In such sunny parts of the forenoon the whole of the sheltered region, apart from the shaded area, has a higher temperature than the open, as may be expected according to BODROFF's theory.

The mornings of the period of April 1946 must in this connection be mentioned as exceptions. For then the sheltered region was colder than the open. This was probably caused by the rainfall during the previous night. As the wind is stronger in the open region than in the sheltered one, rainwater will evaporate more quickly in the former than in the latter region. As a result the temperature will at first be lower in the open than in the sheltered area because of the withdrawal of latent heat from the soil and the crops. Later, however, the heat capacity of the crop and the soil, and also the conduction of heat in the soil will for some time be greater in the sheltered region than in the open, and these factors naturally impede the heating of the air. If our supposition is right this impediment must be so strong that the temperature of the stagnant air above the sheltered region remains lower than that of the air above the open region. Of course the part played in this respect by the soil will become less important as the crop grows.

The sheltered region will also have a higher temperature than the open when a clearing occurs in the afternoon. In this case the soil and the crop will only have been heated slightly before the sky becomes clear, and if this happens not too late in the day, it will still be possible for the whole landscape to be heated by the sun considerably. In other words the balance of heat will remain positive till a later hour than would have been the case if there had been no clouds during the morning. Up to this time the temperature of the stagnant air will also be higher than that of the open region.

The effect will be the stronger, as incoming radiation is stronger. It could be distinctly observed in April and May. In November the conditions were such that the effect of the phenomenon was probably neutralized by the passage of a cold front.

The microclimatic situation in an oak coppice sheltered region during a day or a part of a day with an intermittent cloud deck is closely related to the cases discussed in the first part of this section. We consider an intermittent cloud deck covering about 0,5 of the sky. It is not so much the cloud deck itself as the intermittent insolation which is important.

During the period of May 1946 we found two such days with an intermittent cloud deck consisting of Cu. It appeared that under these conditions the sheltered region did not get definitely colder than the open before it was late in the afternoon. During the readings, which were nearly always made during sunny periods the temperature was nearly in all cases higher in the sheltered region than in the open.

It will be clear that the soil and the crop are heated less on days with a cloud deck of this kind than on days with little cloudiness. Moreover, the heat will spread into the higher layers of the atmosphere when the exposure to the sun is temporarily interrupted, owing to which the soil and the crop will become colder. Therefore till late in the afternoon the balance of heat cannot be but positive during sunny periods and the stagnant air in the sheltered region must at the same time show a higher temperature than the air in the open. As the measurements were made above ground that was all but bare, the latter may also have played a part in putting off the reversal to a later time in the day in the way as discussed in the previous section.

In June 1943 we found days with a heavy cloud deck consisting of Cb, accompanied by gusts of wind, while from time to time there were sunny periods with little wind. The temperature distribution characteristic of the situation with sun and light wind in the sheltered area, proved to present itself rather soon every time after the appearance of the sun.

The data obtained did not supply more details on the temperature during such short periods with sun. No doubt they would have done so if the measurements could have been made more systematically. We think, however, that there are indeed reasons to assume that the conclusions concerning the course of temperature during sunny periods when there is an intermittent cloud deck consisting of Cu, and those concerning the influence of rain shortly before the appearance of a sunny period are also applicable to the situation discussed above.

C. *Temperature in the Daytime under a Heavy Cloud Deck, with Light to Moderate Wind*

Because the characteristic distribution of temperature between two stands on a clear day results from radiation, as we have amply discussed, it is certain that the situation will be quite different under a heavy cloud deck (cloudiness $^{10}/_{10}$).

Under such a cloud deck the differences in temperature between the sheltered and the open area, and those between the observation posts in the sheltered area are always smaller than under any other cloud deck, both in the daytime and at night. The distribution curve of the temperature in the sheltered region is then quite or light, from light to moderate, or strong. Neither here is it possible to draw sharp lines.

Referring to the distribution and course of temperature during a bright day with wind from light to moderate we shall start here with the discussion of the minimum during a clear night with wind from light to moderate.

First it should be remembered that on unclouded evenings with little wind the air above the sheltered region always showed lower temperature than that above the open. In this case the distribution of the temperature in the sheltered region was all but symmetrical with regard to the stands, being as follows: The lowest temperature was found in an area halfway between the two stands. Starting from this area the temperature gradually increased into the direction of the stands as far as places situated at a distance of some meters from the stands. Next to the stands the temperature was again a little lower.

This same distribution in the sheltered area was found back with respect to the nocturnal minima, but now at a lower temperature level, as a consequence of outgoing radiation during the night.

This distribution is to be explained in the following way. The screening-effect of the stand with relation to outgoing radiation is strongest next to the stand (GEIGER 1936, GEIGER 1942), and gradually decreases with the distance to it. Thus half way between two stands outgoing radiation must be strongest and therefore more heat is withdrawn from the stagnant air here than in places where outgoing radiation is to a higher degree counteracted by the stands. Herewith the gradual increase of the temperature minimum into the direction of the stand is explained. This is not the case, however, with regard to the low temperature next to the stands. But we know (KOCH 1934) that a narrow zone of low temperature is also found along forest edges. There it is caused by a slowly descending current of air which has been cooled down owing to the emission of radiating energy by the crowns of the trees. It will be clear that the low minimum temperature next to the stand is to be explained in the same way. In this connection, however, we must assume that KOCH's "nocturnal forest wind" will be stronger and will have a more distinct effect than the cold current of air next to the narrow oak coppice stands. Hence it appears that the effect of this current of air in the oak-coppice sheltered region is only to be noticed distinctly if there is little wind.

When the wind velocity is from light to moderate and radiation meets with little or no obstruction from clouds, the air above the area half way between two stands will become colder than that above the open region. This is, generally speaking, never the case in zones where outgoing radiation meets with obstruction. In the narrow strip along the woodstands, however, there is again a better chance that the air above it will become colder than in the open area. It will be clear that this distribution of the nocturnal minimum entails increased danger of night-frost in certain zones of the sheltered region.

La Cour (1872), Bates (1911) and Bodroff (1936) had already pointed out the increased danger of night-frost between stands. However, it has not appeared to us that these authors have realized the fact that this increased danger is restricted to certain zones only.

Some of our data seem to indicate that the forming of ground fog, under which conditions, as we know, heat is released, may check or neutralize the fall in temperature of the sheltered region with respect to the open. Of course this is only possible when the fog would appear sooner or in a denser form in the sheltered region than in the open. We are not in possession of direct observations regarding this subject. From the measurements of air humidity (see page 137), however, it has appeared that as a rule the air above the sheltered area is somewhat more humid than that above the open. This might indicate that, under certain conditions, fog will appear sooner in the sheltered region than in the open.

Now one may ask into what direction the cold current of air (next to the stand) moves on after reaching the ground. In this respect we cannot give much information, but still there are some facts worth-while of attention. In the first place during the period of April 1943 no distinct difference was observed between the minimum on the post below and on the one next to the stand, whereas we might have expected that the value found below the stand would have to be higher as a result from the fact that in this place less radiation occurs during the night. In the second place we should once more remember the higher temperature found at some distance from the stand. The two facts mentioned contain an indication that the cold air would sink below the oak shrubs of the windscreen. Thus an upward movement must take place in the stand itself, so that in this way an independent system of circulation would form in and close to the stand. This conclusion, however, is in contradiction and wind during the 24 hours of a day. Naturally this daily course will present itself more distinctly the more numerous the readings during the 24 hours are. In our case no more than two readings were made; one in the morning and another in the evening comprising respectively evaporation during the preceding night and during the preceding day. Of course no sharp picture of the daily course of evaporation could be expected on the base of these data but obtaining such had not been our purpose. Yet is was found that, as a result of the diurnal course evaporation is considerably stronger in the daytime than at night. In rainy weather evaporation was also very low or nil. Thus, usually no difference of any importance between the sheltered region and the open could be found in the data bearing on the nights, or in those obtained in rainy weather.

In dry sunny weather, however, distinct differences were observed in all cases. These differences were greater as the wind was stronger, so that in strong wind evaporation was considerably lower in the sheltered region than in the open.

Rather distinct differences were also found between the posts in the sheltered region itself. It seems probable that they were in most cases caused by the differences in wind velocity in these places. As a result the range of the evaporation is greater in the sheltered region than in the open.

Thus it has appeared that the distribution of evaporation is to a high degree controlled by the wind, which is in accordance with the results obtained by LA COUR (1872), BODROFF (1936), and NÄGELI (1943). In light wind, however, the influence of temperature also presents itself. At the same time, however, this influence appears to be small. Also NÄGELI (1943) noticed the influence of temperature on the differences of the evaporation. He found a shifting of the minimum of evaporation with regard to the wind minimum, into the direction of the stand, which was caused by differences in radiation.

5. WIND AND THE WIND REDUCING INFLUENCE OF OAK COPPICE STANDS

When describing the experiment area we have already pointed out that probably not a single part of the sheltered region would be exposed to the full wind when the direction of the latter is perpendicular or almost perpendicular to the longitudinal axis of the stands. This conclusion was based on data obtained from literature (FLENSBORG and NØKKENTVED, 1938 and 1940, and NÄGELI 1943 and 1946).

The only reliable data we ourselves dispose of have come from a 31-m long cross-section between two stands. The measurements were carried out when the wind direction made an angle of about 45° with the longitudinal axis of the stands.

The conclusion stated above is confirmed by these data, naturally only for the situation that has been investigated. We have no reason to suppose, however, this conclusion would not be correct with reference to other cases when the wind was favourable.

Also in other places of this summary some information on the lee in the sheltered region in various wind directions has been given. For instance, we have concluded from the data on temperature that the width of the sheltered zone amounts to only 3 or 4 h in strong wind, when the wind direction forms an angle of about 30° with the stand. In light wind, however, blowing from the same direction, no influence bearing on the distribution of temperature was found, so that these data contain an indication that the windfield of an oak-coppice sheltered region in light wind is essentially different from that in strong wind. According to literature this would be a property of dense windscreens (see page 17).

Also various other data contain indications concerning the class of density of oak coppice stands. For example, the distribution of temperature in the scald zone indicates the absence of a current of air of any importance under the stand, for if this current existed it could hardly be understood that the temperature can become so high next to the stands.

The evaporation curves indicate an evaporation-minimum in or very closely behind the stand and they do not show any indication of a wind minimum at some distance behind the stand (see the evaporation-curve of 2 May 1944 in fig. 25). Therefore we must assume that the wind minimum was also lying closely behind the stand. From the work of FLENSBORG and NØKKENTVED (1938 and 1940) and of NÄGELI (1943 and 1946) it has appeared that also this property is among those belonging to the windfields of dense windscreens.

Naturally these indications are indirect ones. However, our own observations which are of course of a direct nature pointed into the same direction.

From the distribution of temperature in the daytime and the nocturnal minima it had to be concluded that in light wind, of the temperature of the mass of air that lies above the region. The absolute values of the temperature differences which in this connection appear depend apart from the sun's altitude (season) also on the moisture and dust content of the mass of air. The latter conditions and the season being the same, however, the increase of air temperature in the zones in the sheltered area during daytime as well as the fall in temperature during the night would be practically independent of the temperature of the air mass present.

From the statement quoted above a lack of understanding of the existence of the temperature zones found over and over again appears. For that matter, it is to be understood that a layman makes such a statement, as one will feel more comfortable in a sheltered region than in an open one, especially in severe frost and strong wind. This feeling of comfortableness, however, is not a reliable measure to judge on the absolute value of temperature, because in this connection wind and relative humidity also play a part.

We have also to discuss shortly the views held by BODROFF (1936). From the previous pages it will have become clear that our data in many cases were in accordance with BODROFF's views. We have already argued that these views are based on data obtained in the dry Russian steppe, and very probably on averages obtained by means of series of observation during periods of sufficient length. We, however, have always tested the temperature course on separate days.

In doing so it has become clear to us that the reversal, dependent on the cloud deck, sometimes takes place early, at other times late in the afternoon. A reversal early in the afternoon occurs on a day when the sky is cloudless or almost cloudless from morning till night, and during which the air mass undergoes no changes. On days with a heavy cloud deck during the forenoon and in cases when an intermittent cloud deck occurs throughout the day, the reversal takes place late in the afternoon. Therefore the average reversal will take place at a point of time in between. If, in this connection, we take into account the fact that in our country the number of days with a variable cloud deck is greater than in the Russian steppe, we may expect that in our country the mean reversal will take place somewhat later in the afternoon than yonder.

Chapter VIII

Summary and Conclusions

1. An investigation was made into the micro-climatic properties of a cultivated area on sandy soil sheltered by narrow oak-coppice stands. Attention was paid in the first place to the distribution of the air temperature, measured at a height of 2 or 10 cm above the ground. Moreover data were collected on the distribution of air humidity, evaporation and in some cases also of soil temperature and wind.

In this publication measurements made above or in *high* crops are not taken into consideration.

2. A rather elaborate study was made of the literature concerning this subject, from which it has appeared that some general and fundamental insight had already been obtained into the properties of the windfield in the neighbourhood of and between windscreens, chiefly as a result of the efforts of some Danish and Swiss investigators. In the literature we have moreover found ideas, either more or less founded, on some other microclimatic factors.

From the results obtained by the foreign investigators mentioned it could be concluded that, if the wind direction is perpendicular to or almost perpendicular to the oak-coppice stands, not a single point of the oak-coppice hedged area examined will be exposed to the full wind.

3. In the field observations the microclimate of an oak-coppice sheltered area was, during short periods, compared with that of an open area. The differences found were always considered with regard to the prevailing type of weather, the hour of the day, and the time of the year. As to the way in which it was carried out this investigation has therefore been rather of a micro*meteorological* than of a micro*climatic* nature.

4. Concerning the above mentioned climatic factors an insight was obtained into the character and the causes of the existing micro-

being even more or less protected from night-frost. The danger of night-frost will be greatest in two zones, viz. in the first place in the part of the region where the prevention of outgoing radiation resulting from the distance to the stand is practically nil but where the stand still influences the wind considerably, and in the second place in the narrow belt of the descending current of cold air next to the stand, on both sides. *During calm nights only the cold current of air next to the stand will be active. For the rest of a sheltered area it is to be expected that during such nights it will have partly a higher temperature and partly the same temperature than an open area.*

10. A narrow zone with relatively high temperatures proved to exist next to the shaded zone in the daytime. Although many attempts to explain the situation have failed we are to consider the existence of this zone as a reality. The only conclusion with regard to this zone is, that the latter seemed to be connected somehow with the contrast between sun and shade on the ground.

11. The thicker the cloud deck, the smaller the differences in temperature between the two areas and between the different temperature zones in the sheltered area will be. This holds good both for the daytime and for the night.

12. In strong wind the differences in temperature are, as it were, swept away. The differences in temperature only occur in places where the wind is reduced considerably. When studying the differences under these conditions we find the same regularities as have been described above.

13. Generally speaking, we may assume that *absolute* air humidity is higher in a sheltered area than in an open one. When in a sheltered area the temperature is temporarily higher, the *relative* humidity, however, may be lower here than in the open, in spite of the higher absolute humidity.

14. The distribution of evaporation has appeared to depend considerably on the distribution of wind velocity. A local rise in temperature only causes a slight increase in evaporation in that place. *Thus evaporation is usually much smaller in a sheltered area than in an open one.* It needs no demonstration that this is of great advantage to the

crops during periods of drought. This decrease in evaporation, however, may be a disadvantage during the harvest proceedings, when the reaped corn is drying. This causes the complaints of the farmers mentioned in the introduction.

15. Indications were obtained, both in direct and indirect ways, that oak-coppice stands are among the class of dense windscreens as indicated by the Danish and Swiss investigators (see survey of literature). *This means that planting oak-coppice stands is not the most efficient method for obtaining shelter in a region. The same, perhaps a better result might be obtained by planting more pervious windscreens.*

16. It has appeared that an important part of the peculiarities of the distribution and course of temperature air humidity and evaporation in an oak coppice sheltered area may be carried back to the properties of stagnant air. As the wind is in some way and in some degree reduced by any woodstand, it may be assumed that the microclimate found in oak-coppice sheltered regions will return in some form in any sheltered region, depending on the nature of the windfield of the woodstands in the region observed.

In principal the other influences viz. shading and reflection, will also be active in other landscapes. The density and the size of the windscreens will, to a high degree, be decisive for the measure in which these influences will appear.

From the facts mentioned it will have become clear that the results obtained are at the same time both a basis and a motive for investigations in regions that are sheltered by other types of woodstands.

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